PROCMT
User's guide

OFFLINE PROCESSING SOFTWARE
FOR
MAGNETOTELLURIC TIME SERIES

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Used Symbols and Nomenclatura

Mathematical Symbols

Symbol	Nomenclature	Examples
Matrix	bold, capital	**S**
Vektors	bold, lower case	**a**
other Variables	italics, capital or lower case	g_i, v, XY^*
Functions	lower case, normal	$\max_i(...)$, coh(...)
Real part of a complex number		$\Re\{..\}$
Imaginary part of a complex number		$\Im\{..\}$
complex conj. values		Y^*, XY^*
Average value, with or without weight		$\bar{a}$, $\overline{\mathbf{S}}$
indirect computed channels (predicted channels)		$\hat{Z}$, $X\hat{Z}^*$
Iteration-Indices		$\mathbf{S}^{(j)}$, $v^{(0)}$

Conventions in Text

All names, foreign language expressions and references to figures, tables and other text parts are printed in *Italics.* Beside names of persons also names of programs, files, modules, procedures and variables are marked correspondingly.

All words which shall be pointed out especially are printed in **bold**. This is also used for all key-descriptions, menu entries and screen outputs.

The wild cards * and ? are used in the same manner as in the *DOS* operating system. The * stands for any string and the ? for any character. This abbriviation is used especially in connection with file names and sometimes with the names of modules, procedures and variables.

Dereferencing of menu entries or procedures is done with the ´.´ **File.Read RTS.Station B** references to the menu item **Station B** which is to be found under menu item **Read RTS** which finally is to be found under the menu **file**.

Introduction

The program *PROCMT* is a program system for off-line processing of time series recorded with the *Metronix* MT-systems *MMS03e* or *GMS05*. The following main features are implemented:

- Display of raw time series of up to 8 channels
- Display of calibrated time series
- Marking of time segments as bad (time series selection)
- Display of spectra
- Definitaion of any equations (uni- or bivariate)
- Remote Reference
- Computation of cross and auto spectra and impedance tensor
- robust estimation of cross and auto spectra
- Display of apparent resistivity and phase
- Program can read calibration files for fine calibration
- Variable FFT-length up to 4096 data points
- Fully menu operated
- File handler included
- Trend elimination optional

The program can handle a frequency range between $(4096\ \text{sec})^{-1}$ and 8192 Hz. Due to the large bandwidth a splitting into different frequency bands is necessary, which are measured independently at the measurement sites. These frequency bands are computed by the program separately and the results for the different target frequency lines are calculated. Finally, the results for the different bands are combined. This results in one file containing the cross- and auto spectra of all measured channels (E and H) and of all target frequencies.

The time series of the electric and magnetic field components are split into fixed time segments whose length can be determined by the user. Data analysis is done for each time segment resulting in many matrices for each target frequency (up to several hundred) containing the cross and auto spectra of all channels. The number

of segments can be increased as the program also allows a 50 % overlap of the segments.

Normally, the measurements are affected by more or less strong distortions which may cause wrong results. For this reason the second step of data analysis provides a statistical estimation of an average spectral matrix. Several algorithms are implemented and can be selected according to the requirements and the data quality.

Furtheron, *PROCMT* includes options to display the configurations and numerous possibilities to display the recorded electromagnetic fields in time and frequency domain with or without calibration. The display option allows a selection of suitable segments for the data analysis and gives a first impression of the data quality of the measurements.

Also the results of the apparent resistivity and phase versus frequency can be displayed. This provides a quick impression of the results of the different analysis methods. Either bivariate as well as univariate equation sets can be selected (with or without reference station).

The following sections comprise a short summary of the different chapters of this documentation and give an overview about the contents of the documentation.

Chapter 1 explaines the installation and operation of *PROCMT* in detail. Beside the installation and the optimum configuration of a given PC the different screens and menus are explained.

Chapter 2 describes the used measurement methods and systems as well as the geophysical equations which define the combination of the measured electromagnetic fields. Especially, the splitting of the frequency spectra into the different bands is explained. In spite of the program allows the definition of any equation combining the different measurement channels, there exist some of special interest which are also explained here. Additionally, the remote reference mode is demonstrated beside the normal uni- or bivariate single site mode. The intention of this chapter cannot be the complete derivation of the theory, moreeven the background knowledge to understand the further chapters (esp. *chapter 3*) shall be given.

Chapter 3 gives a mathematical description of all algorithms and computing methods used in this program. The first part shows the computation of the spectral matrices which are calculated from the different selected time segments. The analysis of the time segments is performed independently for each segment. By this means for each time segment a different spectral matrix is computed. It is the task

of the algorithms described in the second part to compute an optimum, average spectral matrix for each target frequency from the many, single, raw-spectral matrices (it can be up to several hundreds) using statistical analysis methods. Different methods are shown here which attempt to reach this aim.

Appendix A gives a detailled mathematical description of the transfer functions of the *MMS03E* and the *GMS05* system.

The data formats are explained in the Metronix manual "File Formats of the *GMS05*".

Chapter 1

Operating the Program

1.1 Installation

The installation of the program is very simple: it is sufficient to copy the files *PROCMT.EXE* and *PROCMT.FRQ* into any directory of your choice. When you are in the directory where these two files are installed you can start the program by typing **PROCMT**. However, there are some requirements to the system which shall be described now. Furtheron, the user can adapt the program by using some environment variables (*DOS-Environment*) according to his requirements.

1.1.1 System Requirements

The program *PROCMT* has been developed and compiled using the *JPI Modula Compiler Topspeed 3.1®* under MSDOS 5.0® or higher. The program runs on all AT-compatible computers with 386-processor or higher with minimum 1 MByte of RAM. Due to the very high amount of numerical calculations a *387* coprocessor or better a *486DX* or a *Pentium™* processor is required. A bigger memory with 4 Mbyte or more is highly recommended. The programm runs with a so called *DOS-extender* and profits from the gain of memory.

Enough space for the temporary files and the result-files has to be provided on the harddisk. The required harddisk capacity depends on the amount of data to be analysed. The free harddisk capacity should not be smaller than 5 MByte. The maximum space required is about 10 Mbyte - not included the necessary space to keep the time series files.

1.1.2 Harddisk-Cache Program

When the program is running it will extensively access to data which is stored as temporary files on the harddisk. Therefore, it is highly recommend to install a so called *Cache-program*. Such a program (SMARTDRV.EXE) belongs to the *DOS* system V5.0 or higher - therefore the installation should not be a problem. Please refer to the *DOS* manual. Of course another comparable cache program of a third party distributer could fulfill the same requirements. Again, it should be mentioned that the program accesses several 10,000 times to the harddisk. A cache program increases the speed enormously (more than four times) and reduces the physical harddisk accesses by a multiple.

1.1.3 EMS-Memory

The program runs with a *DOS-extender* in the so called *Protected-Mode*. It therefore requires *Expanded Memory*. An installed driver, for instance *EMM386.EXE*, which is included in the *DOS* should be removed or installed with the *RAM* option.

It can be a line into your *CONFIG.SYS* file like:

DEVICE=C:\DOS\EMM386.EXE RAM

or a similar statement in order to provide some EMS-memory. Please refer to your *DOS* manual for further information.

1.1.4 Environment Variables

The program flow, especially the access to the files, is mainly controlled by a number of environment variables (*Environment*). These variables are set with the *SET*-command of the *MSDOS*-operating system. The best way is to set these variables during the system initialization in the *AUTOEXEC.BAT* file or in a special batch file which also starts the *PROCMT* program. The following chapters give an explanation of all these environment variables .

1.1.4.1 PROCMTDIR

The program searches in this directory for initializing files especially for the file *PROCMT.FRQ*. In case this variable is not found in the environment, the program searches in the actual directory from where *PROCMT* is called.

Note: It is important to set this variable in case *PROCMT* shall be started from another directory. Otherwise the file with the target frequencies (*PROCMT.FRQ*) will not be found by the program and the execution is interrupted with an error message.

1.1.4.2 RTSDIR

Defines the directory where *PROCMT* searches for files containing time series after having started the program. If another directory is selected in order to read a time series file, this directory will be used by the program in the future automatically as long as the program is not terminated or another search path has been selected. If *RTSDIR* is not defined in the environment, the program will start searching for time series files in the directory where you started *PROCMT*.

1.1.4.3 SPMDIR

Defines the directory in which the files containing the cross and auto spectra (**.SPM* or **.EDI* format files) shall be written. In case this variable is not defined the start directory of *PROCMT* will be selected to store the files.

1.1.4.4 SPMTMPDIR

In this directory the spectra which have been computed from the time series are stored. These files exist only temporarily during program runtime. In case this variable is not found the program will look for the *MSDOS* standard variable for temporary files *(TEMP resp. TMP*). In case this variable is also not defined the start directory of *PROCMT* will be selected to store these files.

Note: The program will access these temporary files up to several 10,000 times during the program run. Due to this reason a harddisk cache program (f.i. *SMARTDRV*) should be installed or the directory *SPMTMPDIR* is set to a RAM-disk.

1.1.4.5 PMTTMPDIR

PROCMT uses this directory to write other interim results of the cross and auto spectra. Also these files exist only temporarily. If *PMTTMPDIR* is not found in the environment, the program will not search for the standard directory for temporary files, but use the start directory of *PROCMT*. This is necessary as the temporary files with the cross spectra can become very big (up to 20 MByte) which may exceed the space for temporary files in some systems - especially when the standard directory for temporary files is on a RAM-disk.

Note : The program accesses these temporary files very often. It is therefore recommended to use a cache program for the directory *PMTTMPDIR*, too.

1.1.4.6 PMTCOLOR

This environment variable can be used in order to change the preadjusted colours (grey/blue in text mode and gray/cyan in graphic mode) suitable for a monochrome black and white display. This may be especially necessary when a monochrome or greyscale LC-display is used (laptop-computer) as the different colours cannot be distinguished very well on these displays. Five possible adjustments exist:

- **COLOR** Colour display (grey/blue resp. grey/cyan)
- **MONO** Black letters on bright background
- **MONOINV** White letters on dark background
- **LCD** MONOINV adjustment in text mode and MONO adjustment in graphics mode
- **GMS05** Special adjustment when PROCMT is used with *GMS05*

The special LCD-adjustment causes that text and graphics being displayed black on a bright background. In the standard case (Colour-display) the variable *PMTCOLOR* should be set to **COLOR** or it can be omitted completely as the colour display is selected automatically if *PMTCOLOR* is not found in the environment.

1.2 User Interface

1.2.1 Main Window

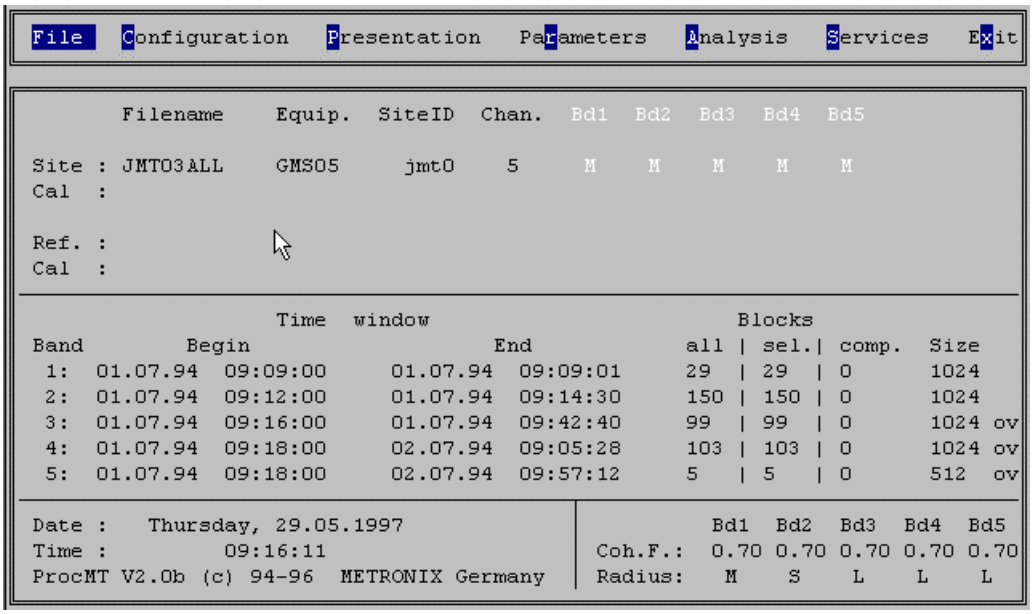

File Configuration Presentation Parameters Analysis Services Exit
Filename Equip. SiteID Chan. Bd1 Bd2 Bd3 Bd4 Bd5
Site : JMTO3ALL GMS05 jmt0 5 M M M M M
Cal :
Ref. :
Cal :
Time window Blocks
Band Begin End all | sel.| comp. Size
1: 01.07.94 09:09:00 01.07.94 09:09:01 29 | 29 | 0 1024
2: 01.07.94 09:12:00 01.07.94 09:14:30 150 | 150 | 0 1024
3: 01.07.94 09:16:00 01.07.94 09:42:40 99 | 99 | 0 1024 ov
4: 01.07.94 09:18:00 02.07.94 09:05:28 103 | 103 | 0 1024 ov
5: 01.07.94 09:18:00 02.07.94 09:57:12 5 | 5 | 0 512 ov
Date : Thursday, 29.05.1997
Time : 09:16:11
ProcMT V2.0b (c) 94-96 METRONIX Germany
Bd1 Bd2 Bd3 Bd4 Bd5
Coh.F.: 0.70 0.70 0.70 0.70 0.70
Radius: M S L L L

Figure 1.1: Main window of PROCMT with menu bar

The upper part of the screen shows the menu bar. The menu will be described in detail later. The rest of the screen represents the main window in which the most important information about the measurement data is displayed. Additional information about the station and channel configuration can be seen via the **Configuration** menu.

In the upper third of the main window the most important information about the time series, which has been read-in is displayed. The user can see the filename of the time series file (without extension) and the type of measurement system (*MMS03e* or *GMS05*). It follows the name of the recording site, the number of the channels connected and finally information about the measured bands. The four lines content the local site RTS file with calibration file and the RTS and CAL file of the reference site (for remote reference).

The status information about the band requires some further explanation:

- **–** There is no data in this band available
- **M** Data available, calibration with theoretical transfer function of the measurement system (model function)
- **C** Data available, calibration with a calibration function which has been gained with the measurement system (calibration files only exist with the *GMS05*)

Furtheron, it can be seen, which bands have been activated for the time series analysis. Those bands are rendered white. Bands with black status signs are available but not disabled for data processing.

NOTE: Normally, in the documentation of the *MMS03e* the bands are numbered 1..4. In order to keep the numbering consistent (same numbers for the *MMS03e* and the *GMS05*), here band 2 corresponds to the original band 1, band 2 corresponds to band 3 of the *MMS03e* and so on. The *MMS03e* is not capable to record band 1 data (frequency range 256 Hz - 8192 Hz) - this can only be done with the *GMS05*.

In the second part of the main window the recording times for all bands are displayed. The times displayed here show the beginning and the end of the period of time during which data has been recorded. If a reference station is loaded these times must not necessarily fit with the original recording times. The ´ true´ times can be seen under the menu item **Configuration.Measurement times**.

The measurement period is set to a multiple of the measurement time of one section of the time series. If, for example, a time window of 49.6 sec was found out and the section size has been set to 2048 points, the time window will be set to a multiple of 2 sec (this is the duration of a recording of 2048 points in band 3; ref. *table 2.1*) and results in a total of 48 sec.

Note: If two stations are read which have no time series recorded at the same time then no measurement times are displayed on the main window.

Behind the measurement times the number of sections of time series which fit into this time window are displayed. Succeeding to that, you will find the number of the selected time sections and the number of the sections analysed. It follows the selected section length and finally the label **ov** in case overlapping time sections have been selected or **ts** if data is recorded in *time slice* mode. The meaning of the overlap and the different informations to the sections is explained later.

Note: The *GMS05* normally records band 1 (256 Hz to 8192 Hz) and band 2 (8Hz to 256 Hz) data in a *time slice* mode (see *GMS05* manual). In this case the lines with the measurement times are marked with **ts** at the end. The displayed end times for *time slice* recording may not be correct. It is also not allowed to increase the time series length (see chapter 1.2.4.3) beyond 1024 points and it is not possible to use overlapping time series (see chapter 1.2.4.2).

On the lower right corner of the main window the adjusted factors for the selective stacking (see *2.2.4.3. selection with adaptive coherency threshold*) and the relative width of the *Parzen*-window are displayed The length of the sections is chosen in the menu **Parameters** and the factors in the menu **Analysis**. Further explanation is given in the corresponding sections of these chapters.

On the lower left corner of the main window the actual time and date is displayed. This display is not refreshed all the time. Only when an output is done in this window or a menu item is selected, time and date will be refreshed.

1.2.2 Menu System

The menu control is achieved by selection of a menu item using the cursor keys (←,↑,→,↓) and pressing the **ENTER**-key or just by typing the bold letters. These hot keys are only valid for the menu item being actually active (frame with double line). Initially the main menu is activated. When typing for instance **F** the file menu will be opened and is now activated.

In the following sections the single menus and submenus will be described in their function and mode of operation. Two menu items of the **Presentation** menu are an exception here, i.e. the presentation of time series (**Time Series)** and the presentation of the transfer functions which have been selected by entering the equations (**Equation**). Both menu items switch to the graphics mode and have a user interface of their own. Therefore, they are not described in subchapters, but have own chapters (see *1.3 The Presentation of the Time Series* and *1.4 The Presentation of the Transfer Functions*).

1.2.3 File Menu

The menu item **File** comprehends all functions to read and write files. All inputs of filenames are done by a selection of files in the input window. As the file input window is used for most of the functions of the **File** menu, it follows a description of this window at first. After that all entries in the **File** menu are described.

1.2.3.1 File selection Window

The title of the window displays which kind of files shall be read in. Below that you can see the actual path name and the files which shall be displayed. If the entry behind **Name** is for instance ***.SPM** only files with the corresponding extension will be displayed. If there is a ***.*** as in the picture printed below, all files will be displayed.

Using the cursor keys and the keys **Home, End, PgUp, PgDn,** a file can be selected which will be read by pressing the **ENTER** key. When typing **ESC** you can leave the window without reading a file.

The input path can be changed by selection of the two dots ("[..]" stands for the previous directory) or by selection of a path name (name is enclosed in brackets).

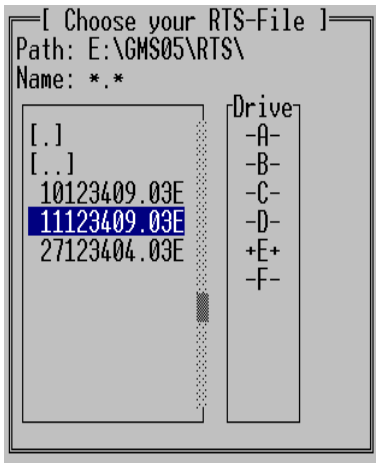


Figure 1.2: File selection window (file selector)

With the **TAB**-key the user can switch from the file selection to the drive selection table. The drives are selected using the same keys as used with the file selection. When pressing **ENTER** the input path will be set to the corresponding drive.

Note: The file selection window only operates properly when the system variable *Lastdrive* is set to the last drive installed in the system; otherwise also drives will be displayed which are not available at all. A second problem may occur in connection with disk drives. In case such a floppy drive is selected and no or a disk is damaged the program will hang. Therefore it is recommended to use *PROCMT* with harddrives (or network drives) only.

1.2.3.2 Read Time Series files

With the menu item **Read Files** a submenu is opened allowing to read the time series and calibration files. After selection of the filename, information about the status and the configuration of the corresponding station will be displayed. Further information is available in the **Configuration** menu (see chapter 1.2.4).

The menu item **Clear all** allows to remove the files. Please note that the station is removed from the PC´ s memory**not** on the harddisk - the file itself is not modified at all. If a file is read in, deletion of the previous station may be omitted. It is sufficient just to read the new file - the old file will be overwritten then.

Note: In any case data access to a file is only a reading one. The original files always keep unmodified. An accidently deletion of a file is impossible by this means.

1.2.3.3 Reading of Calibration Files

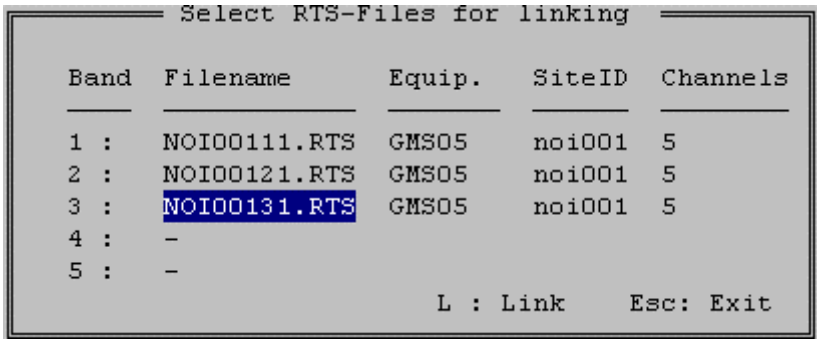
Reading and removing of CAL files into resp. from memory is principially done in the same manner as reading of RTS-files. However, a time series file has to be read before. Only then it is possible to check whether the CAL-file fits with the read time series file. In case a time series file is deleted or overwritten, the corresponding CAL-file will also be removed from memory.

In case the calibration file is not compatible with the station file, i.e. the configuration data of both files do not fit to eachother, an error message is displayed. A message will also be shown in case it is tried to use a Cal-file in connection with *MMS03E* data.

Note: It is possible that calibration data is only available for a part of the bands contained in the RTS-file. Only those bands will be labelled with a **C** in the main window for which calibration data is available. The other bands will be calibrated with the model function (labelled with **M**). It is possible that the calibration file is compatible to the time series file but does not contain information about the recorded data. This might happen for example if the calibration file is gained with notches switched on, the time series in contrast have been recorded with notches switched off.

1.2.3.4 Combination of Time Series Files

The function **Link RTS** allows to link different time series files. Up to 5 files can be entered which will be combined to one single file by this option. For each band one file can be read from the Link RTS window. Just selct one band and press RETURN. The standard file selection window will open and a RTS file can be selected. It is not necessary to enter a file for all stations. In case a station is missing the corresponding band will be set to "not measured". However, care has to be taken that the entered files contain valid data in the frequency band corresponding to the station latter - otherwise an error message will be displayed.


Select RTS-Files for linking
Band Filename Equip. SiteID Channels
1 : NOI00111.RTS GMS05 noi001 5
2 : NOI00121.RTS GMS05 noi001 5
3 : NOI00131.RTS GMS05 noi001 5
4 : -
5 : -
L : Link Esc: Exit

A file can be attached to several bands. For example: the data of the bands 1,2,3 of file X and the data of the bands 4 and 5 of file Y shall be combined in file Z. This is achieved by reading file X into the band s 1, 2, 3 and the file Y into the station 4 and 5. After pressing '**L**' Key linking of the files will start. A message which asks the user to enter a name for the new data file will appear automatically. Just enter a normal 8 letter file name without extension and finish the entry by pressing **ENTER**.

As each time series file contains only one section containing the station and channel configuration data, it is necessary that all entered files have the same configuration.

I.e. all files must have identical channel configurations and also the notch filter and high-pass adjustments must be identical. Of course, it is impossible to link files which have been recorded with different measurement systems (*MMS03e* and *GMS05*). All data which shall be linked must be recorded with the same type of instrument.

If the configuration check has been finalized successfully and no error message has been displayed, you will be asked to enter a name for the new file. The program will append the extension *.RTS* automatically and write the file into the directory from which the last file has been read.

Also when files are linked together the original files will not be modified. In case these files are not used any longer they have to be deleted in the *DOS* command shell.

1.2.3.5 Reading of Spectral Files (*.SPM)

The menu item **Read SPM** allows to read of spectral files (**.SPM* format). The station and channel configurations will be read from the file as far as possible (for instance no recording times are contained in the file) and displayed in the main window as well as under the **Presentation** menu. It is only possible to read one spectral file at the time which, however, may contain data of up to 5 bands. A deletion of spectral files is not provided. When reading a new spectral file or a time series file, the old one will be removed from memory automatically.

1.2.3.6 Reading of Spectral Files (*.EDI)

The menu item **Read EDI** allows to read of spectral files (**.EDI* format). The function of this menu item is the same like **Read SPM.**

Note: After data processing PROCMT stores the resulting cross and auto power spectra in two different file formats. The EDI and SPM files contain the same spectral data. Because the EDI files are in ASCII text format and the SPM files are in binary format reading of SPM files is much faster then reading EDI files. Therefor it is recommended to rather read the SPM format files.

1.2.3.7 Save PROCMT configuration

With the menu item **Save Config** the parameter settings and selection of time series windows can be stored. The configuration file will have the same name like the first time series file with the file extension *.CFG. This option should be used after selection of time series. Because the selection of time series windows take some time a reprocessing can be done much faster when the selection is stored in a *.CFG file.

1.2.3.8 Read configuration file (*.CFG)

With the menu item **Read Config** a complete configuration (time series file with parameter settings and time series selection) which was stored before with **Save Config** menu camn be read.

1.2.4 Display of Station and Channel Configuration

The **Configuration** menu offers a couple of possibilities to obtain a more detailed overview about station and channel configuration than given in the main window.

1.2.4.1 Channel Configuration

Channel Parameters Station B: 11123409

Channel	Labels	Pregain	Postgain	Distance	Angle
1 :	Ex	3	1	103	0
2 :	Ey	3	1	158	0
3 :	Hx	10	1	--	0
4 :	Hy	30	1	--	0
5 :	Hz	3	1	--	0
6 :	--	1	1	--	0
7 :	--	1	1	--	0
8 :	--	1	1	--	0

Press <ESC> to exit !

Figure 1.3: Channel configuration window

The menu item **Channel Config.** presents the channel configuration of each station read in. The window provides the following information for each of the eight channels for a selected station:

- *Label* The channel name: it can be an electrical (**E**) or a magnetical (**H**) sensor which is aligned in N/S (**x**), E/W (**y**) or vertical (**z**) direction. Therefore the channel names **Ex, Ey, Hx, Hy, Hz** exist.
- *Pregain* The preamplification of the measurement instrument can be selected separately for each of the channels. At the *MMS03e* it can be 1, 3, 10, 30, 100 or 300. At the *GMS05* it can be 1 or 16
- *Postgain* The postamplification (factor 1, 4, 16 or 64) is only to be found in connection with the *GMS05*. It is set to 1 when the *MMS03e* was used.
- *Distance* The probe distance shows the spacing between the two electric field probes of an E-dipol.
- *Angle* The angle represents the deviation of the sensor spread from the predefined main direction (North) in degree. The **Ex-**channels normally point to the North (0°) and the **Ey-**channels to the East (90°).

1.2.4.2 Notch and High-pass Configuration

The menu item **Notch/High-pass** indicates the configuration of the notch filters and of the high-pass in a separate window (see below). The high-pass can be switched ' on' or ' off' . If the notch filters are switched on, the corresponding notch frequency will be displayed - if they are switched off a dash (-) is shown.

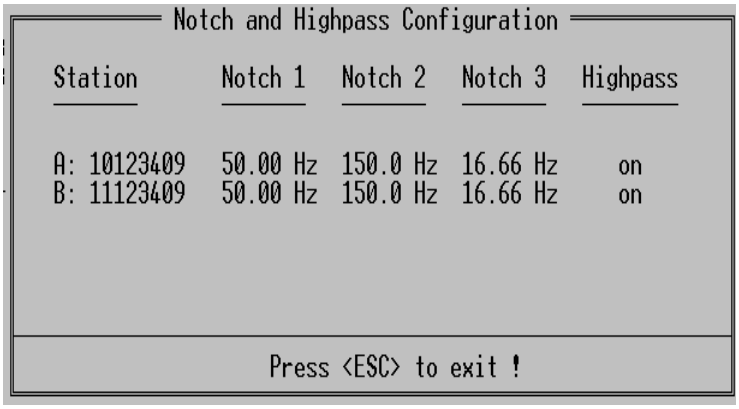


Figure 1.4: Window to display the notch and high-pass configuration

Note: It has to be considered that the notch frequencies of the *MMS03e* cannot be read from time series files. Due to that reason the frequency 50 Hz is always assumed for notch 1, 150 Hz for notch 2 and 16.667 Hz for notch 3. These frequencies are also assumed when calculating the model function.

1.2.4.3 Target Frequencies

The menu item **Frequencies** opens a window in which the selected target frequencies can be displayed. Not all 60 possible frequencies must be used necessarily - a part of them can be shown as **not used.** After the index number follows the frequency in Hertz or seconds, than the number of the target line, the radius as a number of target lines (Fourier frequencies) and finally the number of the band belonging to the frequency.

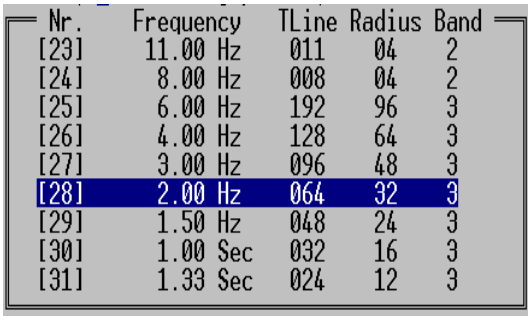


Figure 1.5: Window to display and edit the adjusted target frequencies

With the cursor keys (↑,↓) different frequencies can be chosen in the window. When pressing the key **E** the selected frequency can be edited and replaced by any other. Input format is here the common nomenclature for floating point numbers ([+|–]nnn.nn[E[+|–]nn][S]). Normally, the input is regarded as a frequency in *Hertz*. However, it is also possible to enter values for periods in **sec**. just be adding an **S** as the last character after the float number. Pressing of **RETURN** will delete the old frequency and sort the new frequency into the list. Pressing **ESC** will abort the input mode without modifying the list. In case the entered frequency is greater than 8192 Hz or smaller than $(1/4096 \text{ sec})^{-1}$ this frequency will be sorted at the beginning or the end of the list and set to **not used.** By this means frequencies can be removed from the list. If a new frequency shall be added to the list without deletion of a used frequency, it is sufficient to select a "**not used**" frequency if available. The maximum number of frequencies in this list is 60.

Note: It is only possible to enter the frequencies, all the other displayed parameters are computed automatically. It is recommended rather to use a standard DOS editor to changed the frequencies in the file PROCMT.FRQ. The file format is described in the seperate Metronix manual "*File Formats of GMS05"*. Any changes of the frequency list done in PROCMT will change also the frequency file PROCMT.FRQ.

1.2.4.4 Recording Times

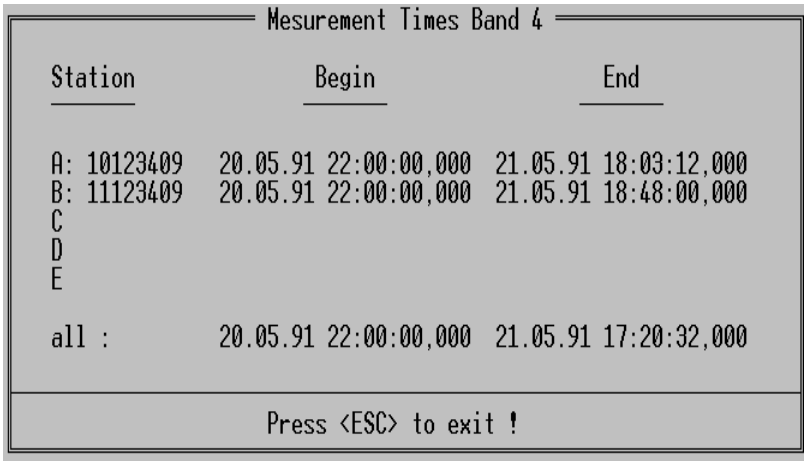


Figure 1.6: Window to display the recording times for all stations

Via the menu item **Measurement times** the user obtains information about the recording times of all bands. In contrast to the main window, here the real recording times are displayed. The item **all:** the start and stop time of the time window is displayed. Hereby the same conditions concerning the section length are valid as already discussed at the display in the main window (ref. *Chapter 1.2.1*).

1.2.5 Presentation menu

The two most important functions of the **Presentation** menu, **Time series** and **Equations** will be explained in separate chapters (*1.3* and *1.4*) because they run in the graphics mode and are much more complex in operation than the other menu items.

The equation input on one hand is used to define those transfer functions which shall be displayed under menu item **Presentation.Equations** and on the other hand to define the equations which shall be used to calculate the multiple coherency which is required for some of the stacking algorithms. At first the input of univariate equations is described and than the more complex one of the bivariate equations. Please refer to *chapter 2* to get more information about the geophysical equations.

1.2.5.1 Univariate Equations

Univariate equations have the form $Z=aX$, where Z and X are any two channels. Later the transfer function $a=Z/X$ will be presented versus the target frequencies (see *Chapter 1.4*). At the equation input beside the channels Z and X it is also decided whether the complex transfer function will be presented as a plot of real and imaginary part or as a plot of apparent resistivity and phase.

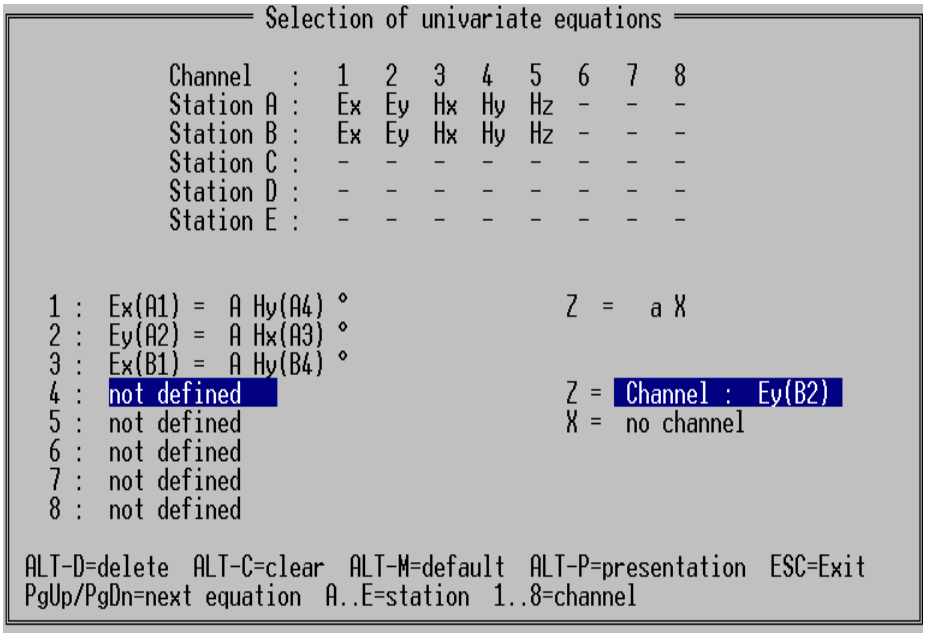

Selection of univariate equations
Channel : 1 2 3 4 5 6 7 8
Station A : Ex Ey Hx Hy Hz - - -
Station B : Ex Ey Hx Hy Hz - - -
Station C : - - - - - - - -
Station D : - - - - - - - -
Station E : - - - - - - - -
1 : Ex(A1) = A Hy(A4) °
2 : Ey(A2) = A Hx(A3) °
3 : Ex(B1) = A Hy(B4) °
4 : not defined
5 : not defined
6 : not defined
7 : not defined
8 : not defined
Z = a X
Z = Channel : Ey(B2)
X = no channel
ALT-D=delete ALT-C=clear ALT-M=default ALT-P=presentation ESC=Exit
PgUp/PgDn=next equation A..E=station 1..8=channel

Figure 1.7: Input window for univariate equations

The window in which the univariate equations will be entered (*Fig. 1.8*) consists of four main sections.

The upper part of the window is a matrix showing the actual channel setup of all the 8 channels of all 5 stations. A ´-´ means that no channel has been connected. All channels which have a valid channel label can be used for the equation input.

The middle left part of the window serves to display all entered equations and allows a selection of the equation which should be entered next. The selection is done with help of the **PgUp** and the **PgDn** keys. The actual equation will be rendered resp. displayed inversely. Up to 32 equations can be defined. The display will always show a section of 8 equations. An equation labelled with a "°" will be presented as amplitude and phase curve, an equation not labelled will be shown as a plot of real and imaginary part. The default is amplitude / phase presentation.

The middle right part of the window serves to enter the actual equation which has been emphasized in the equation list. The first input section is used to enter the channel on the left side of the equation, the second input section below is used to enter the right part of the equation. The corresponding input section is selected with the cursor keys (↑↓). The channel input is done with the keyboard by entering the name of the station first (keys **A**, **B**, **C**, **D** or **E**) and then the number of the channel (keys **1**...**8**). If the channel is occupied, beside the entered station and channel number (for instance **A4**) also the channel label will be displayed (**Ex**, **Ey** , **Hx**, **Hy** or **Hz**). In case the selected channel was not occupied a double question mark (**??**) will be displayed as an error message. If both channels have been entered correctly the equation will be shown on the left side.

In the lower part of the window you will find a "Help"-section indicating all other possible key combinations. In detail those are:

- **Alt-D (*delete*)** Deletes the actual (emphasized) equation.
- **Alt-C (*clear*)** Deletes all equations.
- **Alt-M (*default*)** Deletes all equations and defines the standard MT equations automatically (*Ex=aHy* und *Ey=aHx*) for all stations.
- **Alt-P (*presentation*)** Toggles the display mode for the actual equation between real/imaginary and amplitude/phase display
- **ESC** oder **RETURN** Terminates the equation input. Both keys have the same function.

Note: The input window for univariate equations allows the definition of all possible combinations of two different channels as an equation. It is not checked whether the equations make sense or not. In any case the result will be presented under the menu entry **Presentation.Equation**.

1.2.5.2 Bivariate Equations

Bivariate equations have the form *Z=aX+bY* where *Z, X* und *Y* represent any three channels. Later the estimate value of the transfer function

$$a = \frac{ZX^* \cdot YY^* - YX^* \cdot ZY^*}{XX^* \cdot YY^* - XY^* \cdot YX^*}$$

respectively

$$b = \frac{ZY^* \cdot XX^* - XY^* \cdot ZX^*}{XX^* \cdot YY^* - XY^* \cdot YX^*}$$

will be displayed over the target frequencies. When entering the equation, beside the channels *X,Y* and *Z,* it is also determined whether the complex transfer function *a* or *b* will be presented (the corresponding letter will be displayed in capitals) and whether it shall be presented as real/imaginary or amplitude/phase plot.

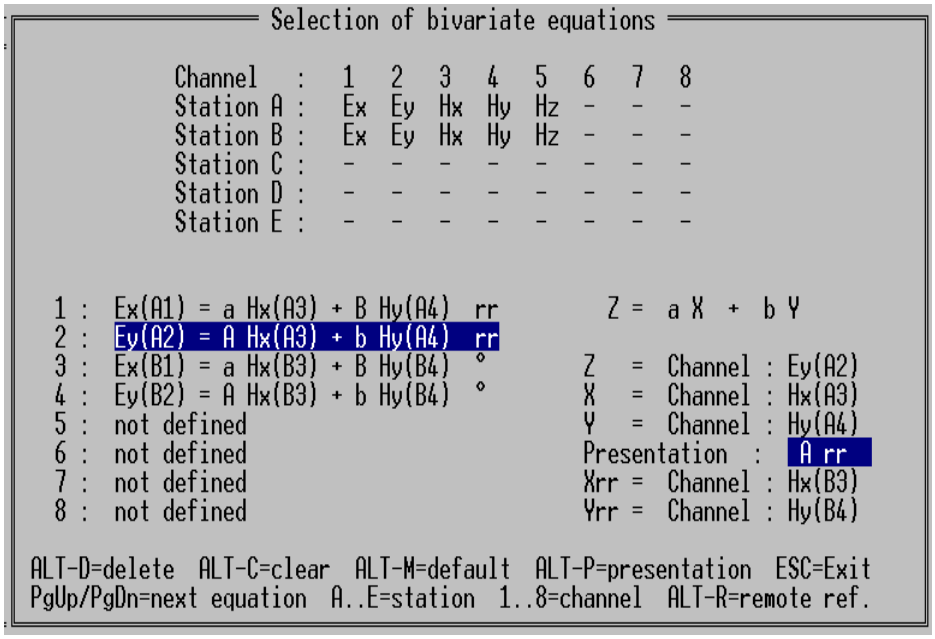

Selection of bivariate equations
Channel : 1 2 3 4 5 6 7 8
Station A : Ex Ey Hx Hy Hz - - -
Station B : Ex Ey Hx Hy Hz - - -
Station C : - - - - - - - -
Station D : - - - - - - - -
Station E : - - - - - - - -
1 : Ex(A1) = a Hx(A3) + B Hy(A4) rr
2 : Ey(A2) = A Hx(A3) + b Hy(A4) rr
3 : Ex(B1) = a Hx(B3) + B Hy(B4) °
4 : Ey(B2) = A Hx(B3) + b Hy(B4) °
5 : not defined
6 : not defined
7 : not defined
8 : not defined
Z = a X + b Y
Z = Channel : Ey(A2)
X = Channel : Hx(A3)
Y = Channel : Hy(A4)
Presentation : A rr
Xrr = Channel : Hx(B3)
Yrr = Channel : Hy(B4)
ALT-D=delete ALT-C=clear ALT-M=default ALT-P=presentation ESC=Exit
PgUp/PgDn=next equation A..E=station 1..8=channel ALT-R=remote ref.

Figure 1.8: Input window for bivariate equations

Additionally, there is a possibility to define equations with a reference station (*remote reference)*. This requires the input of two more channels X_r and Y_r. For the transfer functions in this case it is

$$a = \frac{ZX_r^* \cdot YY_r^* - YX_r^* \cdot ZY_r^*}{XX_r^* \cdot YY_r^* - XY_r^* \cdot YX_r^*}$$

respectively

$$b = \frac{ZY_r^* \cdot XX_r^* - XY_r^* \cdot ZX_r^*}{XX_r^* \cdot YY_r^* - XY_r^* \cdot YX_r^*}.$$

The meaning of the input window corresponds almost with that of the univariate equations (see previous section). In the following description only the differences between the univariate and bivariate input window will be mentioned.

Instead of two channels you have to enter three resp. five channels. The actual equation is displayed on the left side if all channels have been entered correctly. As an additional function you have the possibility to define an equation with a reference station

- **Alt-R (*remote reference*)** Switches from normal (bivariate) mode to the *remote reference* mode.

This requires two more channels (normally H-channels of a second station). Equations according to the *remote reference* method are marked on their right side by an **rr**. The transfer function will be displayed always as an amplitude/phase plot.

Note: Any possible bivariate equations can be entered with any possible channel combination. No check is done whether the equations are meaningful or not. However, the result will be calculated according to the above standing formulas and also be presented.

1.2.6 Parameters of Data Analysis

The menu **Parameter** comprises all possible setups to control data analysis. The setups met here will influence the first part of data analysis and the stacking algorithms are influenced indirectly. A part of the setup (size of section and overlap mode) also influences the display of the time series, especially for the selection of time windows for data analysis. The effects for the display and selection of time series windows are explained in section *1.3 The display of time series.*

Note: All possible setups which can be done in the **Parameter** menu must be done **before (!)** the display of time series if the default setup is not used. After the selection of time windows or after time series analysis these setups may not be changed. Otherwise all interim results (the window selection resp. the temporary spectral matrices) will be lost!

1.2.6.1 Selection of the Active Bands

All bands which contain data will be activated for the data analysis initially. The menu item **Toggle Band** allows an exclusion of single bands. Sometimes it may happen that the program deactivates bands (not rendered in the main window) in spite of valid data exists. This happens especially when switching from the sequentiel to the parallel mode or vize versa. Those bands must be reactivated manually again. Activating of bands without valid data is not possible anyway.

1.2.6.2 Overlapping Windows of Time Series

The overlap mode for the time series windows is activated on standard. With help of the menu item **Overlap** this option can be toggled for each band separately. It is recommended to activate the overlap at least if only a few data for a specific band is available (i.e. band 5). The activated option "overlapping windows" is indicated in the main window behind the number of blocks with the shortform **ov**. The number of time windows changes depending on this option (double or half) and is actualized in the main window correspondingly.

Note: Overlap can not be activated for band 1 and band 2 when they are recorded with the *GMS05* in *time slice* mode. The time slice is indicated by the shortform **st** behind the numbert of blocks.

1.2.6.3 Length of the Time Series Sections

The section size is preselected to 1024 data points for the bands 1..4 and to 512 data points for band 5. Bigger sections normally lead to somewhat better results as the FFT resolution is improved. In any case the data processing is faster. Especially the amount of time required for stacking is reduced. As normally only a few data is available for band 5, the preselected window length is only 512 data points. With help of the menu item **Block size**, different window sizes can be selected (128, 256, 512, 1024, 2048 or 4096).

Note: The length of time series sections is limited to a maximum of 1024 if time series are recorded in *time slice* mode with *GMS05*. The *time slice* mode is indicated by the shortform **st** behind the numbert of blocks.

1.2.6.4 Width of the Parzen-Window

The width of the *Parzen*-window is preselected to a large radius (L, large) for bands 3, 4, 5, medium for band 1 and small radius (S, small) for band 2. The size of the radius in band 1 and band 2 have been selected smaller in order to reduce the effects of the electromagnetic noise caused by the powerlines to the target frequencies. The menu item **Radius** allows to select the width of the *Parzen*-window as shown below:

- **S** (*small*) small radius
- **M** (*medium*) medium radius
- **L** (*large*) large radius
- **XL** (*extra large*) extra large radius

Note: Only a relative and not an absolute radius is fixed. This means that the exact size of the *parzen*-window results from the target frequency and the selected relative radius. The ratio of radial frequency and target frequency of a band is constant.

1.2.7 Data Analysis

Via the menu entry **Analysis.Analysis RTS** the analysis of the time series will be performed according to the algorithms presented in *chapter 3.1* (trend elimination, *Hanning*-window, *Parzen*-window, etc.). The adjustments which have been done in the **Parameters** menu will be respected here.

The progress of the data analysis is indicated in the middle part of the *main window* under **Blocks Comp.** Hereby the number of analysed time series sections is displayed. Sections which have been rejected during the presentation of the time series will be counted also, but they are not analysed. When having finished the time series analysis the number of the analysed sections will be displayed under **Block. Comp.**

The interim results (spectral matrices for all analysed time series sections and all target frequencies) are stored in temporary files. This data is used by the stacking algorithms in order to compute a stacked matrix for each target frequency

according to the algorithms presented in *chapter 3.2*. The different methods to compute the spectral matrices are collected under the menu entry **Analysis.Estimate SPM**. Before starting the computation it is necessary to have defined the bivariate equations (see *chapter 1.2.6.2*). This is required as most of the stacking algorithms use the *multiple coherency* (see *chapter 3.2.1*).

The last menu entry **Coh. Factor** allows to modify the factors for the stacking algorithms with adaptive coherency threshold. The factor determines the number of sections which will be respected during the stacking - the sections with the highest coherency will be selected. The preadjusted coherency threshold of 0.70 is a good compromise between a high degree of freedom and the rejection of outliers for most of the measurements. For time series which have a high amount of noise a smaller facter (up to 0.1) can improve the result significantly.

1.2.8 The DOS-Shell

When selecting the menu item **Services.DOS Shell** the program will switch back to the operating system command line without terminating the *PROCMT* program. All usual *DOS* commands and programs can be performed here. By entering **EXIT** you will return to *PROCMT*.

1.2.9 Termination of PROCMT

The program is terminated with the menu item **Exit** or the key combination **ALT-X**. Before the termination of the program and return to **DOS** the security query has to be answerded with **y.**

1.3 Time Series Presentation

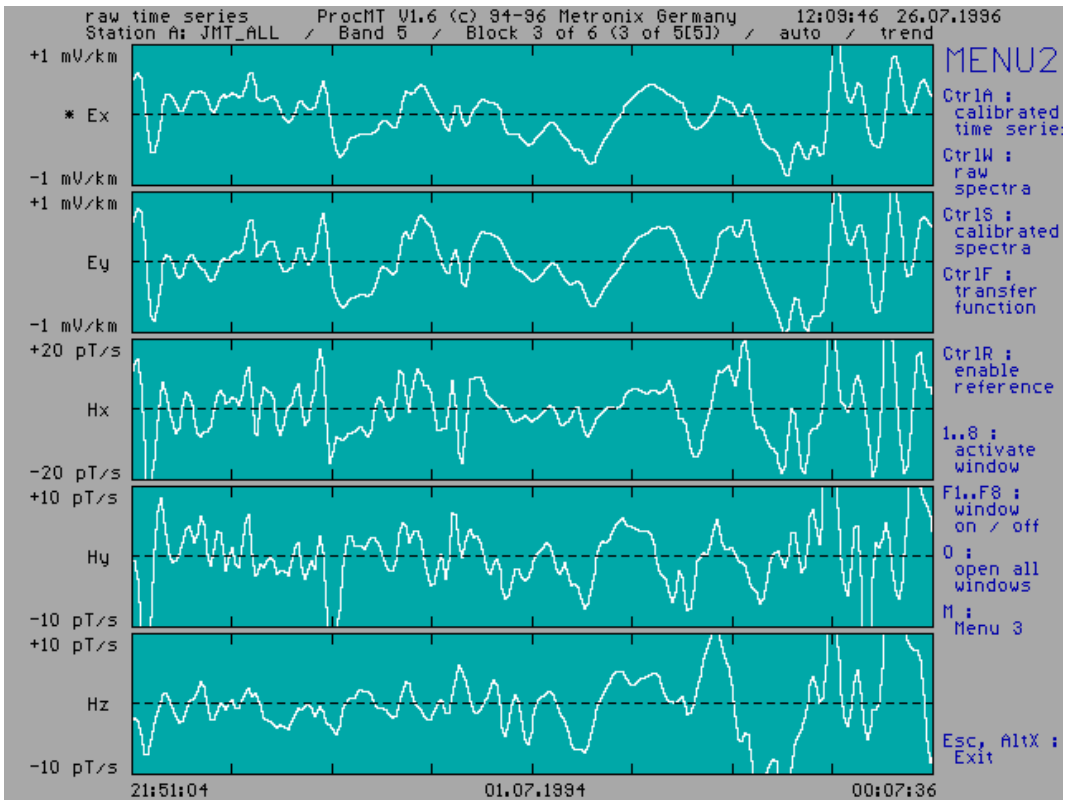


Figure 1.9: Presentation of the measurement data as time series

The presentation of the time series mainly serves two aims. First of all the data quality can be checked. For this purpose a couple of different display modes beside the standard time series mode are available which allow to display spectra and calibrated data as well as the comparison of the data with a reference station. On the other hand, single sections of the time series which are obviously affected by noise can be marked as bad and excluded for the further processing.

1.3.1 Screen Setup

The screen can be split into five sections:

- the title line (first upper text line)
- the status line (second upper text line)

- the menu display (on the right side of the screen)
- the horizontal axis labels (on the lower border of the screen)
- the window where the time series and spectra are displayed incl. vertical axis labels on the left side

At first the single components are described in more detail. It follows an overview about the function and control of the display.

1.3.1.1 Title Row

The title row shows beside the version No. the actual date and time as well as the kind of display mode. Date and time will be always refreshed when a part of the screen or the window contents is drawn. The following display modes exist:

- raw time series
- calibrated time series
- raw spectra
- calibrated spectra
- transfer function

1.3.1.2 Status Line

The status line shows some information related to the displayed data. First it is displayed whether the station or the channel mode is activated. In the station mode the station index (A..E) and the file name will be displayed additionally. Furtheron, the selected band, the number of the actual display section as well as the number of all display sections is indicated. The number of sections and the total number of sections for data analysis follow in brackets (). In [] brackets the number of sections which have been selected for data analysis are shown. A further explanation about the difference between display sections and sections for the data analysis is given in *chapter 1.3.2.4 The Selection of Time Series Sections.*

In case the automatic scaling or the trend elimination is activated this will be indicated by a special indicator at the end of the status line (*auto, trend*).

1.3.1.3 Menu

All available functions are listed on the right side of the screen. As the amount of available functions cannot be listed in one column, the menu is subdivided into three columns which can be switched with the key **M**. The menu only serves as a list of the available commands with a short description of their function.

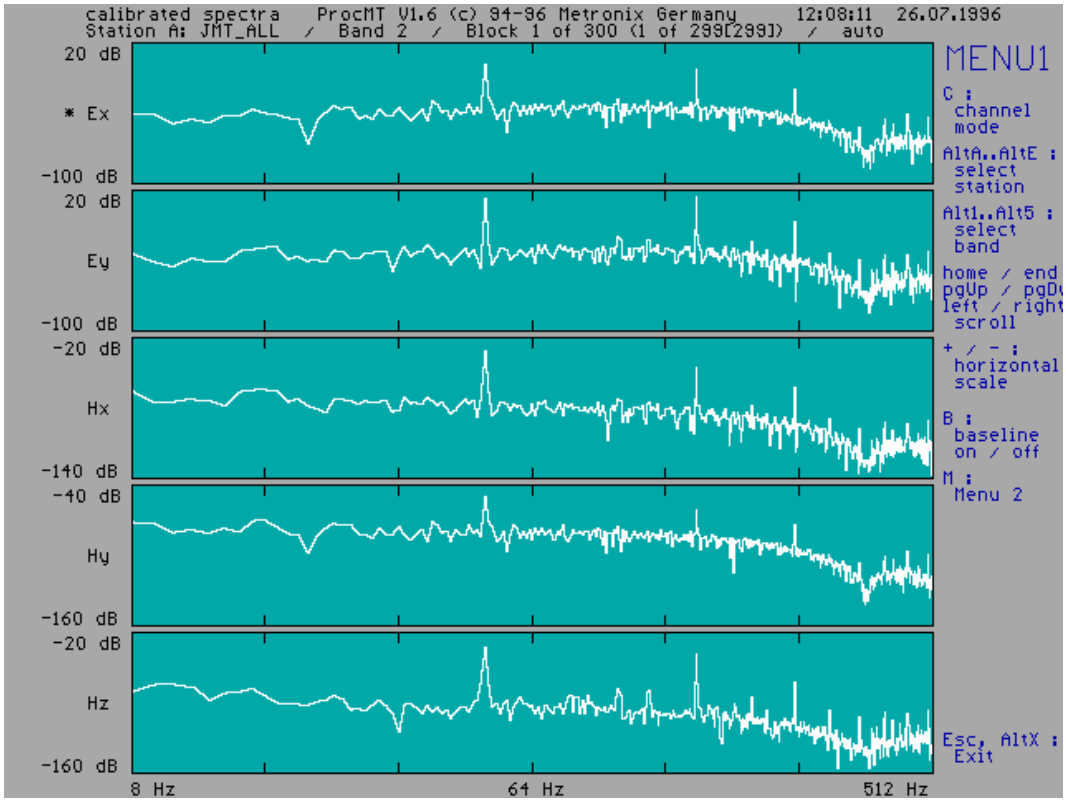


Figure 1.10: Display of the measurement data as calibrated spectra

The display always shows the function being presently active. It may change depending on the activated presentation mode. For example a scaling is not possible if the spectra is displayed and by this means the automatical scaling or manual scaling option is not availabe in the menu.

1.3.1.4 Scaling and Axis Labels

The vertical axis labels show the upper and lower window border for each window. The lowest row in the display will show the start and stop time of the presented

recording display window in case the time series mode has been selected. In the middle of this row you will find the corresponding date. If inside of a display section the time oversteps 0.00h the displayed date will belong to the start time. The horizontal resolution (i.e. number of data points) is not indicated.

Note: When changing the number of data points in a window, the number of data points of all windows will change. In order to avoid confusions between the slice of time series displayed in the window and the slice of time series used for the analysis we will distinguish in futere between **time series slice** if the display in a window is meant and **time series section** if the data for the analysis is meant.

Note: As mentioned before in *time slice* mode of the GMS05 only single time slices of 1024 points and no continous time series are recorded. For that reason the displayed times for band 1 and band 2 may not be correct.

1.3.2. Presentation Modes

1.3.2.1. Presentation of Time Series (Ctrl-T: raw time series)

This mode shows the data as they have been recorded (**.RTS* bzw. **.03E*).

1.3.2.2. Presentation of Calibrated Time Series (Ctrl-A: calibrated time series)

In order to calibrate the data the time series first will be released from a possible mean deviation from the x-axis (trend elimination). Then it will be transformed into frequency domain, divided by the theoretical or measured calibration function and transformed back to time domain.

In frequency domain some more data manipulations are done. So, for instance, only the first half of the frequency band is taken when the data is transformed back to time domain.

The multiplication with a *Hanning*-window prior to the Fourier-transformation is not performed in order to avoid a distortion of the time series at the window´ s edges. This may produce noise in the higher frequency range after retransformation into time domain caused by discontinuities on the edge of the time window. The calibrated time series is released from these distortions as the high frequency lines are not used for the backtransformation.

Another manipulation is done with the band 2 spectra. The amplitudes of the electromagnetic noise caused by powerlines normally exceed those of the natural signal significantly. By this means it is often not possible to observe the natural signal activity in the time series of this band. Therefore, the frequency lines of the 16 Hz, 50 Hz, 100 Hz and 150 Hz incl. their direct neighbor lines are set to zero. Again, it should be mentioned that this is only done for the data display and not for the data processing.

1.3.2.3. Display of Spectra (Ctrl-W: raw spectra)

First the time series are released from a systematic deviation from the x-axis (trend-elimination) and then multiplied with a *Hanning*-window. It follows the transformation into frequency domain (FFT). The transformation is always done for sections with 1024 points independently from the horizontal resolution of the displayed time series and also independently from the section size set in the menu **Parameters**.

1.3.2.4. Display of calibrated Spectra (Ctrl-S: calibrated spectra)

This mode does not differ much from that of the non calibrated spectra. The spectra are divided by the theoretical or measured calibration function.

In this display mode it is

$$0\text{dB} = 1\frac{\text{mV}}{\text{km}\cdot\sqrt{\text{Hz}}} \qquad \text{for electric field channels}$$

$$0\text{dB} = 1\text{nT} \qquad \text{for magnetic field channels}$$

1.3.2.5. Display of the Transfer Function (Ctrl-F: transfer function)

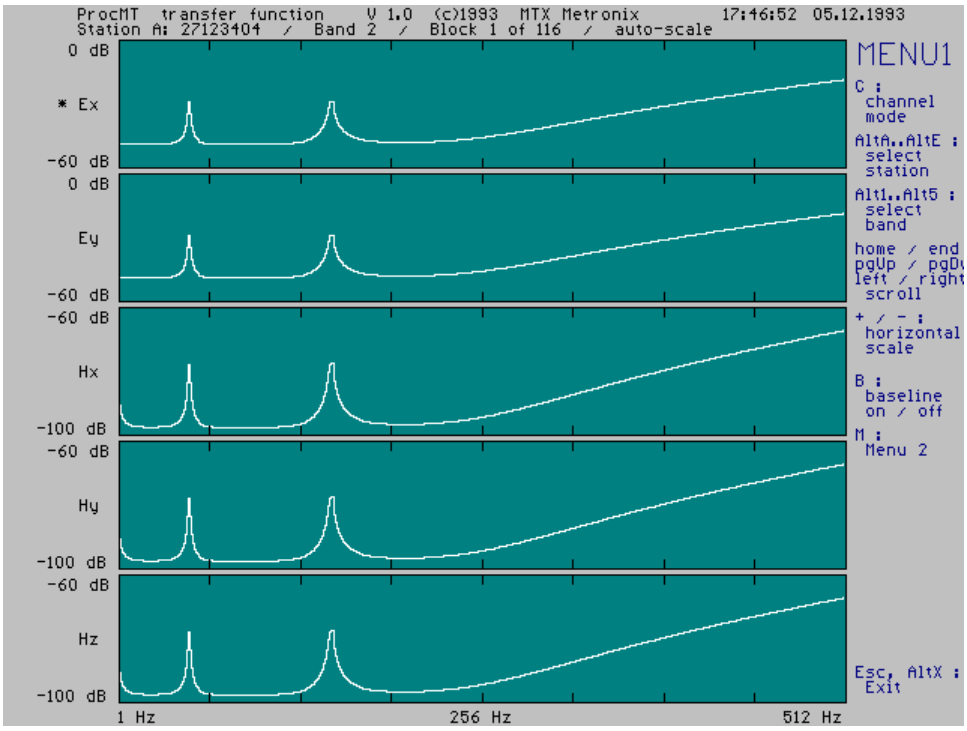


Figure 1.11: Display of the transfer function of the measurement channels

Here not the transfer function itself but its reciprocal is displayed. The transfer function is identical for all time sections of a band.

1.3.2.6. Adding a Reference Station (Ctrl-R: reference station)

The first station (station A) is considered as the reference station. In each window beside the time series or spectra of the selected station (white line), the data of the reference station are presented (yellow line).

Note: Only colour screens allow a proper distinction of the two curves. LCD or monochrome displays provide the same colour for remote station and reference station.

1.3.3. Window- and Screen Configuration

1.3.3.1. Changing the Displayed Band (Alt-1..5: select band)

Allows to change the displayed band. Only bands can be selected for which data is available.

1.3.3.2. Station Mode (S: station mode)

All channels of one station are displayed. The key combinations **ALT-A** to **ALT-E** select the station which shall be displayed.

1.3.3.3. Channel Mode (C: channel mode)

Only one channel of all stations is displayed. The key combinations **ALT-F1** to **ALT-F8** select the channel that shall be displayed.

1.3.3.4. Selection of a Station (Alt-A..Alt-E: select station)

Allows to change the displayed station in station mode. The keys have no meaning in channel mode. Only those stations can be selected which have been selected with the menu item **File.Read RTS** in the main program.

1.3.3.5. Selection of a Channel (Alt-F1..Alt-F8: select channel)

Allows to change the displayed channels in the channel mode. The keys have no meaning in the station mode. Only channels with valid data can be presented.

1.3.3.6. Zeroline (B: baseline on/off)

Switches zeroline (dashed line in the window) on or off

1.3.4. Window Selection and Scaling

1.3.4.1. Open resp. Close a Window (F1..F8: open/close window)

Hereby the window with the corresponding channel index (1..8) will be opened or closed in station mode. In the channel mode the window with the corresponding station will be opened or closed (toggle function). Windows for which no data is available cannot be opened.

1.3.4.2. Open all Windows (O: open all windows)

Opens all windows.

1.3.4.3. Select a Window (1..8: select window)

The active window is marked by a "*****" on its left side. This is important for two functions which refer to the active window:

- The virtical scaling using the cursor keys ↑ und ↓ (see next chapter).
- Change of channel polarisation **Ctrl-P** (see chapter *1.3.2.4*).

1.3.4.4. Vertical Scaling (↑,↓: increase/decrease vertical scale)

Values can be defined manually for the borders of a window which are symmetrical to the zero axis (same absolute value, different sign). The contents of the window and the border values displayed on the left side of the window are adapted accordingly. Only the active window which is indicated by a ´ *´ will be modified and only time series can be scaled manually. The automatical scaling will be always activated for spectra.

1.3.4.5. Automatical Scaling (A: enable/disable autoscale)

Activates resp. deactivates the automatical scaling (toggle function). The limits of the window are selected as small as possible whereby the curve is displayed

completely beside some few outliers in the window. All windows are scaled independently from eachother. When the contents of a window changes, the limits of a window will be rescaled automatically. If the automatic scaling is activated, the cursor keys (↑,↓)have no function. In the spectra display the automatic scaling is always activated.

1.3.4.6. Trend-Elimination (T: enable/disable trend Elimination)

Activates resp. deactivates the trend elimination. The average of the displayed window is set to zero. This option may used be more frequently when band 4 or band 5 data is displayed - the time series here often have a greater deviation from the zero-axis. The automatical, and the manual scaling as well, only allow a ´ symmetrical´ scaling (same distance between upper and lower limit from the x-axis). By this means such time series cannot be displayed in high resolution without trend elimination.

1.3.4.7. Horizontal Resolution (+ / –: inc./dec. horizontal scale)

Modifies the horizontal resolution. Using the ´+´ key will decrease the number of displayed data points (zoom in); the ´-´ key will increase it (zoom out). The max. resolution corresponds to the size of the adjusted length of a time series section but will not increase 1024 data points. In case overlapping mode has been adjusted, the max. resolution will be half of the length of a time series section selected in the main screen. A horizontal scaling can only be done if time series are displayed, the spectra will be always presented in a resolution of 512 frequency lines per interval.

1.3.4.8. Next/previous Time Series Slice (←, →: scroll one block)

The cursor keys (→ and ←) will switch to the next resp. previous section of the time series. The number of the section displayed and the total number of all sections will be shown in the status display.

1.3.4.9. Jump Five Time Series Slices (PgUp, Pgdn: scroll five blocks)

This option allows to jump to the next or to the previous five section using the **PgUp** and **PgDn** keys.

1.3.4.10. First Time Series Slice (Pos 1: select first block)

Pressing the **HOME** key will display the first slice of a time series.

1.3.4.11. Last Time Series Slice (Ende: select last block)

Pressing the **END** key will display the last slice of a time series.

1.3.5. Special Functions

1.3.5.1. Change of Menu Bar (M: change menu)

Pressing the ´**M**´ key will switch from the first to the second, from the second to the third or from the third to the first menu bar. This is necessary as the high amount of functions implemented in the display mode cannot be explained on only one menu bar.

1.3.5.2. Screen Hardcopy (Alt-H: hard copy)

Copies the contents of the display into a file. The precise data format is given in the Metronix manual "*File Formats*". The file will be written into the directory which has been defined with the *PROCMTDIR* environment variable. Up to 99 screen hardcopies are possible and they are named with *PROCMTTS.H01* to *PROCMTTS.H99*. These files can be printed on each printer which is compatible to the *EPSON®-ESC* sequences. During the creation of the file no other command can be entered.

1.3.5.3. Change of Polarity (Ctrl-P: change channel polarisation)

Allows to change the polarity of a specific channel (which has been activated by the ´*****´**)**. This option is very useful in case a faulty field set up of the sensors has been done accidently. The option will only be performed for the band selected and therefore must be repeated for all bands when necessary. The data to be modified can have a length of up to some MBytes and the polarity change may last a while during which no other interactions are possible. A corresponding Note on the upper left corner of the screen is given. Please note that this option will modify the file on the harddisk!

1.3.5.4. Selection of Time Series Sections (space: select block)

Pressing the **SPACE-**bar allows the selection resp. rejection of single sections of time series. In case a section has been rejected this will be indicated by a cross and this section will not be respected in data analys. Pressing the **SPACE-**bar again will delete the cross and the time series section is selected again.

Special care has to be provided when selecting the time series sections. The max. possible horizontal scaling should be chosen here. The size of the selected sections is defined in the main window. By this means it may happen, that when marking a time window as bad, also the previous or the next window is marked in case the section size is larger than the window size. This may happen if the section size is 2048 or 4096 data points as only max. 1024 points can be displayed.

If the overlap mode has been selected, the marked sections which overlap in the displayed window will be excluded from the data processing.

Note: The selection of time series sounds more complicated than it really is. The simplest way is to follow this scheme: at first the max. possible horizontal scale is selected by pressing the ´-´ key several times. Then one observes all time series sections and marks those which seem to be disturbed. When having reached the end and one thinks that not enough or too many have been deselected one can just jump to the beginning and select or deselect more sections. The **SPACE**-bar operates as a toggle switch.

1.3.5.5. Deselect All Blocks (Ctrl-B: deselect all blocks)

All sections are deselected for the data processing. This option allows to proceed differently at the data selection. Instead of excluding sections with strong noise you here will include those sections which you want to select for data processing by pressing the **SPACE**-bar.

1.3.5.6. Select All Blocks (Ctrl-N: select all blocks)

By pressing **Ctrl-N** you select all blocks for the data processing. This option will delete all deselections which have been done previously.

1.3.5.7. Quit Display Mode (Alt-X, Esc: exit)

Quits the time series display. The graphic mode will be left and the text mode (main screen) will appear.

1.4 Presentation of Transfer Function

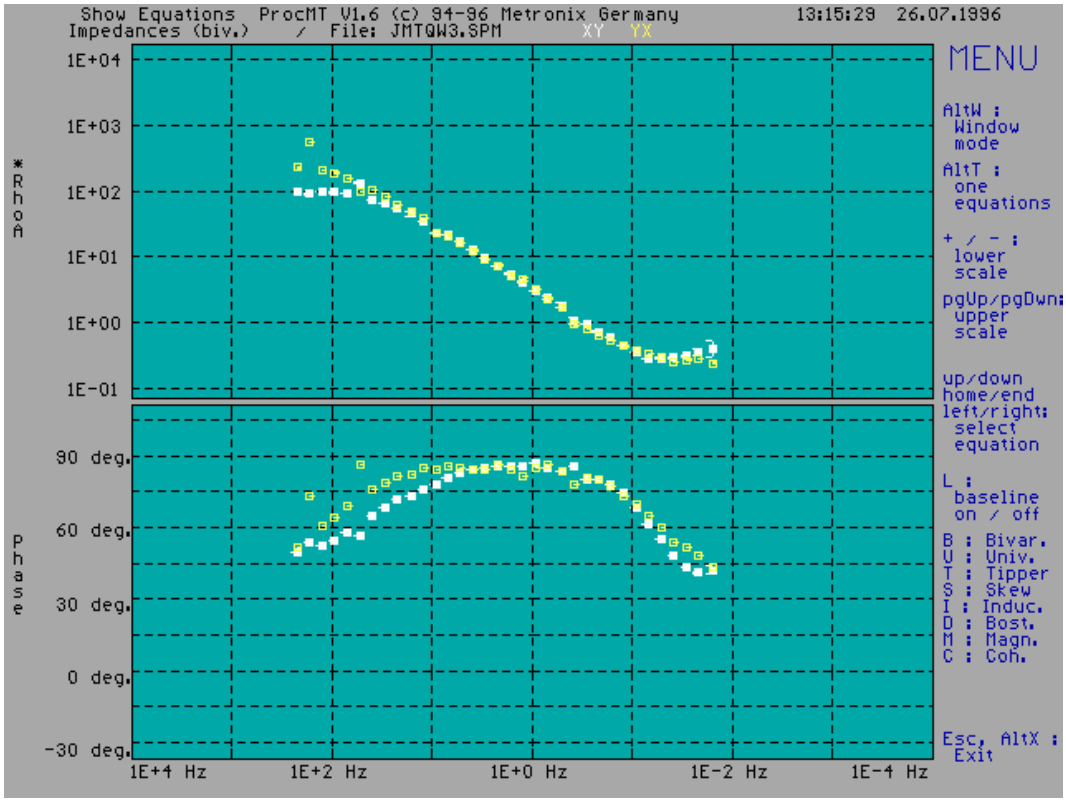


Figure 1.12: Presentation of the transfer function

The display of the transfer function allows a quick check of the results of the data analysis. The transfer functions will be calculated for the entered uni- resp. bivariate equations (see section 1.2.6) and the apparent resistivity and phase will be presented as amplitude and phase resp. real and imaginary part versus frequency. Please refer to *chapter 2.2* to the calculation of error bars.

1.4.1 Screen Setup

The screen can be split into 5 sections:

- the title line (first upper text line)
- the status line (second upper text line)
- the menu display (on the right side of the screen)
- the horizontal axis description (on the lower edge of the screen)
- the windows in which the transfer functions are displayed with their vertical axis labels

The following sections describe the single components in more detail.

1.4.1.1 Title Line

Beside the version number, the title line shows the actual date and time. Date and time are actualized when a new window is drawn.

1.4.1.2 Status Line

The status line shows the kind of equation (bivariate or univariate) which is presently presented and the name of the data file (without path name).

1.4.1.3 Menu

The menu shows all available functions with the keystrokes to invoce them. Functions which are not available in actual display mode will not be indicated. For instance, the display mode "Display of two equations in one window") is only available with a horizontal window configuration. Correspondingly, the key **ALT-T** with the short description of its function only appears in the menu bar when horizontal window mode has been selected.

1.4.1.4 Scaling and Labels of the Axis

The lowest line of the screen shows the horizontal window-axis labeling. The window is scaled logarithmically with a range from 1.0E+4 Hz to 1.0E-4 Hz. The powers of ten are indicated by vertical lines and the grid which can be deactivated resp. activated with the **B**-key (toggle function).

The vertical scaling is also logarithmically in case real and imaginary part or the amplitude is displayed. If the phase is displayed the vertical scale will be a linear one. The gridding has a distance of 10° then. The vertical scale of the active window can be changed by the **+/-** and the **PgUp / PgDn** keys. The axis labels on the left side of the window will be adapted.

1.4.2. Window and Screen Configuration

1.4.2.1. Change Number of Windows (Alt-1..Alt-8: number of windows)

Definition of the number of window pairs which are displayed on the screen (real and imaginary part resp. amplitude and phase, side by side). This definition is only valid for horizontal window setup.

1.4.2.2. Change Window Configuration (Alt-W: window configuration)

At the vertical window setup, only two windows will be displayed which are located among one another. The upper one displays the amplitude or the real part, the lower one the imaginary part or the phase of an equation. At the horizontal configuration both windows are displayed side by side and up to 8 equations can be displayed simultaneously. The key combination **ALT-W** toggles between the two possible window configurations.

1.4.2.3. Presentation of two equations (Alt-T: two equations)

In the vertical configuration you can select the display of one equation or two equations per window. Always two succeeding equations will be displayed then. This mode may be of special interest if you want to present both polarisations of the apparent resistivity and phase curve in one display. The result of the first equation appears in white colour with the boxes filled out. The result of the second equation is presented in yellow open boxes. If more than two equations are selected you may use the ↑ and ↓ keys to select the next.

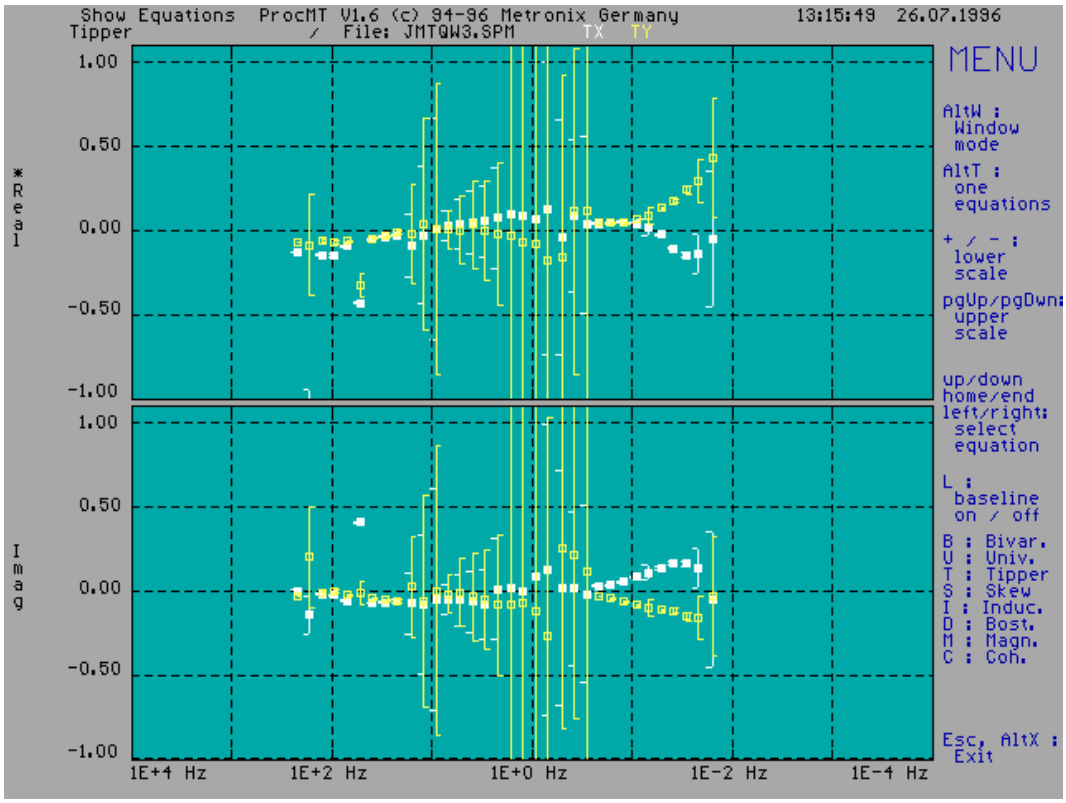


Figure 1.13: Presentation of tipper function

1.4.2.4. Show Bivariate Equations (Alt-B: bivariate equations)

Pressing the **ALT-B** key displays the bivariate equations.

1.4.2.5. Display of Univarite Equations (Alt-U: univariate equations)

Pressing the **ALT-U** key displays the univariate equations.

1.4.2.6. Enable / Disable Grid (B: grid on/off)

The **B**-key toggles the gridding on or off

1.4.3. Window Selection and Scaling

1.4.3.1. Window Selection (↑ / ↓ / ← / →: window selection)

Selection of the displayed equations and marking the active window. With the left and right cursor key the left or right window can be selected in the horizontal display mode. With the cursor up and cursor down keys the window of a specific equation can be activated (for scaling purposes). The active window is indicated by a ´ ***** . If more equations are selected than windows displayed, an up or down scrolling is performed then.

1.4.3.2. Upper Scaling (+ / –: upper scale)

Using the + or - key will change the upper scaling of the window. The contents of the window is modified correspondingly. Only the active window (marked by a *****) can be rescaled.

1.4.3.3. Lower Scaling (PgUp / PgDn: lower scale)

Using the PgUp or PgDn key will change the lower scaling of the window. The contents of the window is modified correspondingly. Only the active window (marked by a *****) can be rescaled.

1.4.4. Special Functions

1.4.4.1. Screen Hardcopy (Alt-H: hard copy)

Copies the contents of the display into a file. The precise data format is given in *Metronix manual "File Formats"*. The file will be written into the directory which has been defined with the *PROCMTDIR* environment variable. Up to 99 screen hardcopies are possible and they are named with *PROCMTEQ.H01* to *PROCMTEQ.H99*. These files can be printed on each printer which is compatible to the *EPSON®-ESC* sequences. During the creation of the file no other command can be entered.

Chapter 2

Introduction to Magnetotellurics and Measurement Instruments

In this chapter a short overview about the geophysical background and the equations which define the combination of the magnetic and electric field components is given. In the following the two measurement systems *MMS03e* and *GMS05* are described and their correlation with the program is shown up. The file format of the time series, the calibration and the splitting of the frequency spectra into the different frequency bands is shown.

2.1 Introduction into Magnetotellurics

The basis of the magnetotelluric equations are electromagnetic fields which can be described by the Maxwell equations. The Maxwell equations for homogenous relations in the quasi static approximation i.e. without displacement currents are:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{H}}{\partial t} \quad [2.1]$$

$$\nabla \times \mathbf{H} = \mu_0 \, \sigma \mathbf{E} \quad [2.2]$$

$$\nabla \cdot \mathbf{E} = 0 \quad [2.3]$$

$$\nabla \cdot \mathbf{H} = 0 \quad [2.4]$$

E is the electrical field in $\left[\frac{V}{m}\right]$

H is the magnetical field in $[T]$

σ is the electrical admittance in $\left[\frac{S}{m}\right]$

μ_o is the magnetic permeability, $\mu_o = 4\pi 10^{-7}\left[\frac{Vs}{Am}\right]$

ω is the radian frequency, $\omega = 2\pi f$ in $[Hz]$

From these relations a linear equation system for the relationship between electrical and magnetical fields can be derived in the frequency domain in form of:

$$\begin{aligned} E_x(\omega) &= Z_{xx} \cdot H_x(\omega) + Z_{xy} \cdot H_y(\omega) \\ E_y(\omega) &= Z_{yx} \cdot H_x(\omega) + Z_{yy} \cdot H_y(\omega) \end{aligned} \quad [2.5]$$

These linear relationships are valid if a quasi homogenous wave geometry and a mainly 2-dimensional field is assumed ($H_Z \approx 0$, i.e. $H_Z << H_X$ und $H_Z << H_Y$).

The equation system [2.5] is solved using the least square method (*LSQ*), where the error ΔE is minimized.

$$E_x = Z_{xx} \cdot H_x + Z_{xy} \cdot H_y + \Delta E_x \quad [2.6]$$

$$E_y = Z_{yx} \cdot H_x + Z_{yy} \cdot H_y + \Delta E_y \quad [2.7]$$

The equations 2.6 resp. 2.7 contain two complex unknown quantities (Z_{xx} and Z_{xy} resp. Z_{yx} and Z_{yy}); this requires at least two complex Fourier coefficients of the spectra H_x, H_y and E_x resp. E_y, in order to determine the unknown Z-elements. However, more Fourier coefficients are comprehended in order to minimize noise. This is achieved using a *Parzen*-Window ($p(i)$=parzen(i), see *chapter 3.1.2.1*). As result for the elements of the impedance tensor one obtains from equation 2.6 :

$$Z_{xx} = \frac{\sum_{i=1}^{n} p(i)H_{yi}H_{yi}^{*} \cdot \sum_{i=1}^{n} p(i)E_{xi}H_{xi}^{*} - \sum_{i=1}^{n} p(i)H_{yi}H_{xi}^{*} \cdot \sum_{i=1}^{n} p(i)E_{xi}H_{yi}^{*}}{\sum_{i=1}^{n} p(i)H_{xi}H_{xi}^{*} \cdot \sum_{i=1}^{n} p(i)H_{yi}H_{yi}^{*} - \sum_{i=1}^{n} p(i)H_{xi}H_{yi}^{*} \cdot \sum_{i=1}^{n} p(i)H_{yi}H_{xi}^{*}} \quad [2.8]$$

$$Z_{xy} = \frac{\sum_{i=1}^{n} p(i)H_{xi}H_{xi}^{*} \cdot \sum_{i=1}^{n} p(i)E_{xi}H_{yi}^{*} - \sum_{i=1}^{n} p(i)H_{xi}H_{yi}^{*} \cdot \sum_{i=1}^{n} p(i)E_{xi}H_{xi}^{*}}{\sum_{i=1}^{n} p(i)H_{xi}H_{xi}^{*} \cdot \sum_{i=1}^{n} p(i)H_{yi}H_{yi}^{*} - \sum_{i=1}^{n} p(i)H_{xi}H_{yi}^{*} \cdot \sum_{i=1}^{n} p(i)H_{yi}H_{xi}^{*}} \quad [2.9]$$

and from equation 2.7 :

$$Z_{yx} = \frac{\sum_{i=1}^{n} p(i)H_{yi}H_{yi}^{*} \cdot \sum_{i=1}^{n} p(i)E_{yi}H_{xi}^{*} - \sum_{i=1}^{n} p(i)H_{yi}H_{xi}^{*} \cdot \sum_{i=1}^{n} p(i)E_{yi}H_{yi}^{*}}{\sum_{i=1}^{n} p(i)H_{xi}H_{xi}^{*} \cdot \sum_{i=1}^{n} p(i)H_{yi}H_{yi}^{*} - \sum_{i=1}^{n} p(i)H_{xi}H_{yi}^{*} \cdot \sum_{i=1}^{n} p(i)H_{yi}H_{xi}^{*}} \quad [2.10]$$

$$Z_{xy} = \frac{\sum_{i=1}^{n} p(i)H_{xi}H_{xi}^{*} \cdot \sum_{i=1}^{n} p(i)E_{yi}H_{yi}^{*} - \sum_{i=1}^{n} p(i)H_{xi}H_{yi}^{*} \cdot \sum_{i=1}^{n} p(i)E_{yi}H_{xi}^{*}}{\sum_{i=1}^{n} p(i)H_{xi}H_{xi}^{*} \cdot \sum_{i=1}^{n} p(i)H_{yi}H_{yi}^{*} - \sum_{i=1}^{n} p(i)H_{xi}H_{yi}^{*} \cdot \sum_{i=1}^{n} p(i)H_{yi}H_{xi}^{*}} . \quad [2.11]$$

The Index i stands in the equations 2.8 to 2.11 for the i-th Fourier-coefficient of the transformed time series.

Instead of the impedence tensor **Z**, the admittance tensor **W** can be calculated also:

$$\begin{aligned} H_x &= W_{xx} \cdot E_x + W_{xy} \cdot E_y + \Delta H_x \\ H_y &= W_{yx} \cdot E_x + W_{yy} \cdot E_y + \Delta H_y \end{aligned} \quad [2.12]$$

Impedance and admittance tensor result in:

$$\mathbf{Z} = \begin{pmatrix} Z_x & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \quad \text{and} \quad \mathbf{W} = \begin{pmatrix} W_{xx} & W_{xy} \\ W_{yx} & W_{yy} \end{pmatrix} \qquad [2.13]$$

Assumed that the field components do not contain any noise ($\Delta E = 0$ bzw. $\Delta H = 0$), the following relationship between impedance and admittance tensor is valid:

$$\mathbf{Z} = \mathbf{W}^{-1} \qquad [2.14]$$

2.2 Equations for PROCMT

2.2.1 Bivariate Equations

In the program *ProcMT* and also in the further documentation the arrangements to determine the impedance and admittance tensor are standardized and written down in the compressed notation:

$$Z = a\,X + b\,Y + \Delta Z \qquad [2.15]$$

$$a = \frac{ZX^* \cdot YY^* - YX^* \cdot ZY^*}{XX^* \cdot YY^* - XY^* \cdot YX^*} \qquad [2.16]$$

$$b = \frac{ZY^* \cdot XX^* - XY^* \cdot ZX^*}{XX^* \cdot YY^* - XY^* \cdot YX^*} \qquad [2.17]$$

The crossings of two spectra:

$$XY^* = \sum_{i=1}^{n} p(i)\, X_i Y_i^* \,. \qquad [2.18]$$

are named cross spectra. In case a field component is crossed with itself (i.e.: $X=Y$) it is called auto spectra. *Z*, *X* and *Y* are three given components of the electric or magnetic field. *a* and *b* are called equation parameters in the following. In case of the equations 2.6, 2.7 resp. 2.12 these are the elements of the impedance resp. admittance tensor.

The confidence intervals for the computed parameters $a \pm \Delta a$ and $b \pm \Delta b$ are determined according to SCHMUCKER[85] by

$$|\Delta a|^2 < \frac{4}{\nu - 4} g_F(\nu) \frac{\varepsilon^2 \, ZZ^*}{XX^* \left(1 - r_{xy}^2\right)} \qquad [2.19]$$

resp.

$$|\Delta b|^2 < \frac{4}{\nu - 4} g_F(\nu) \frac{\varepsilon^2 \, ZZ^*}{YY^* \left(1 - r_{yx}^2\right)} \qquad [2.20]$$

There is $g_F(\nu)$ the value of the *Fischer-function* ν with a security of the confidence interval of 68%. The error ΔZ becomes small if the measured field component Z is optimally in line with $a \cdot X + b \cdot Y$. Accordingly, the error becomes small with a high coherency of both components and big with a low coherency. In the errror calculation this is respected with the residue:

$$\varepsilon^2 = 1 - \frac{a \cdot XZ^* + b \cdot YZ^*}{ZZ^*} \qquad [2.21]$$

Only in case the field components X und Y are independent from each other, the parameters can be determined from the equation set [2.15] with good reliability. Due to this reason the error calculation also respects the coherency between the channels X and Y:

$$r_{xy}^2 = r_{yx}^2 = \frac{XY^* \cdot YX^*}{XX^* \cdot YY^*} \qquad [2.22]$$

2.2.2 Remote Reference Method

A second possibility to minimize especially the noise of the magnetic field components is using so called *Remote Reference* techniques. When using the normal arrangements (equations 2.15 to 2.17) the autospectra of all channels are affected by a so called *Bias* which increases the values artificially. This is caused by noise which is correlated in the auto spectra. The noise of the two channels, however, is not correlated in the cross spectra.

In order to determine the tensor elements, the conjugate complex components of the magnetic fields are replaced by the corresponding components of a remote station (*Remote Reference*) (CLARK[78]). The original arrangement [2.15] is not

modified; only the computation of the parameters [2.16 und 2.17] is modified as follows:

$$a = \frac{ZX_r^* \cdot YY_r^* - YX_r^* \cdot ZY_r^*}{XX_r^* \cdot YY_r^* - XY_r^* \cdot YX_r^*} \qquad [2.23]$$

and

$$b = \frac{ZY_r^* \cdot XX_r^* - XY_r^* \cdot ZX_r^*}{XX_r^* \cdot YY_r^* - XY_r^* \cdot YX_r^*} \quad . \qquad [2.24]$$

The components X_r and Y_r are the channels of the reference station corresponding to the original channels *X* and *Y*. The confidence intervals for the computed parameters $a \pm \Delta a$ and $b \pm \Delta b$ are determined according to the equations 2.19 to 2.22 by:

$$|\Delta a|^2 < \frac{4}{\nu - 4} g_F(\nu) \frac{\varepsilon^2 \cdot ZZ^*}{X_r X_r^* \cdot \left(1 - r_{xy}'^2\right)} \qquad [2.25]$$

and

$$|\Delta b|^2 < \frac{4}{\nu - 4} g_F(\nu) \frac{\varepsilon^2 \cdot ZZ^*}{Y_r Y_r^* \cdot \left(1 - r_{yx}'^2\right)} \qquad [2.26]$$

Hereby ε^2 is computed according to equation 2.21 with the parameters resulting from equations 2.23 and 2.24. Furtheron it is:

$$r_{xy}'^2 = r_{yx}'^2 = \frac{XY_r^* \cdot YX_r^*}{XX_r^* \cdot YY_r^*} \quad . \qquad [2.27]$$

2.2.3 Univariate Equations

In case the main elements (Z_{xx} and Z_{yy}) are equal or near to zero, the equation arrangements derived above (2.15 bis 2.17) can be simplified to univariate arrangements:

$$Z = a X + \Delta Z \qquad [2.28]$$

$$a = \frac{ZZ^*}{XX^*} \qquad [2.29]$$

The confidence interval $a \pm \Delta a$ results from a modification of the equations of the bivariate arrangement [2.19 bis 2.22]:

$$\varepsilon^2 = 1 - \frac{a \cdot XZ^*}{ZZ^*} \qquad [2.30]$$

$$|\Delta a|^2 < \frac{2}{\nu - 2} g_F(\nu) \frac{\varepsilon^2 \, ZZ^*}{XX^*} \qquad [2.31]$$

The factor 4 in equation [2.19] is replaced by a factor 2, as the equation arrangement [2.28] only contains two unknown values (real and imaginary part of *a*), in contrast to four unknown values (real and imaginary part of *a* and *b*) [2.15].

2.2.4 Presentation of the Parameters

Generally, the apparent resistivity (ρ_A) and phase curve are presented versus frequency which results from the equations

$$\rho_A(\omega) = \frac{\mu_0}{\omega} |a(\omega)|^2 \qquad [2.32]$$

and

$$\Phi(\omega) = \arctan\left(\frac{\Im\{a(\omega)\}}{\Re\{a(\omega)\}} \right), \qquad [2.33]$$

respectively from the above equations where *a* is replaced by *b* in order to obtain the other polarization. It also exists the possibility to present the real and imaginary part versus frequency.

2.3 Measurement Systems *GMS05* and *MMS03e*

The field components necessary to compute the cross spectra are recorded by the *Metronix* instrumets *GMS05* and *MMS03e*. The magnetic field sensors are aligned in North/South (H_X), East/West (H_Y) and in vertical (H_Z) direction. Each of the electrical fields are measured between 2 poles which are aligned from North to South (E_X) and East to West (E_Y).

The frequency range which can be recorded by the instruments is split into five (*GMS05*) resp. four (*MMS03e*) frequency bands. Hereby band 1 can only be recorded with the *GMS05*. All the other frequency bands correspond to eachother. Please note that band 1 in the *MMS03e* manual corresponds with band 2 in this manual. When performing the data analysis not the whole frequency band is used which has two reasons: first of all each target frequency line shall be correlated to a specific frequency band, on the other hand the corners of a frequency band cannot be used because a *Parzen window* is applied to each target frequency that may not exceed the measurement range of the bands. Due to this reason only the range given under *target frequencies* in *table 2.1* is used. *Table 2.2* gives further information about sampling rates, measurement times etc.

Band	Measurement Range	Target Frequencies
1	16384 Hz ... 32 Hz	8192 Hz ... 256 Hz
2	512 Hz ... 1 Hz	256 Hz ... 8 Hz
3	16 Hz ... 32 sec	8 Hz ... 4 sec
4	2 sec ... 1024 sec	4 sec ... 128 sec
5	64 sec ... 32768 sec	128 sec ... 4096 sec

Table 2.1: Frequency bands: measurement ranges and used frequency ranges

Input data for the program *PROCMT* is time series recorded with the measurement systems *GMS05* or *MMS03e* (*.RTS resp. *.03E). A third data format exists in connection with the calibration of the measurement channels: the calibration files (*.FCT) which contain the calibration data of the *GMS05*. A complete discription of the file format is given in the Metronix manual "*File Formats"*.

The calibration of the measured time series is required in order to eliminate the influence of the measurement system (filters, gains etc.). For this purpose the data is divided by the calibration function of the instrument in frequency domain. Beside the possibility to calibrate the measurement data with a measured calibration function (*GMS05* only) there exists the possibility to apply a theoretical model function to the raw data. This model function is also integrated into the program *PROCMT*. A complete description of the theoretical model function of the *GMS05* and *MMS03e* is given in *Appendix A*.

Chapter 3

Methods of Data Analysis

The analysis of the time series can be divided into two main sections. First the time series are split into sections of a fixed preselectable size. For each of these sections the first part of data analysis is applied independently. For each section a matrix containing all cross and auto spectra is computed for a number of determined target frequencies. This procedure is repeated for all measured frequency bands.

During the second main section of data analysis the optimum matrix is computed from all the present matrices. This procedure is repeated for all target frequency lines. In the following the first part of data analysis is called *Analysis of Time Series* while the second part is named *Computation of the Spectral Matrix*.

3.1 Analysis of Time Series

In this chapter an explanation is given how a single spectral matrix is computed from a specific time series section for all target frequency lines. *Figure 3.1* shows an overview about the first part of data analysis. First of all the calibrated spectra are computed for all channels and succeeding to that the spectral matrix is computed for each target frequency.

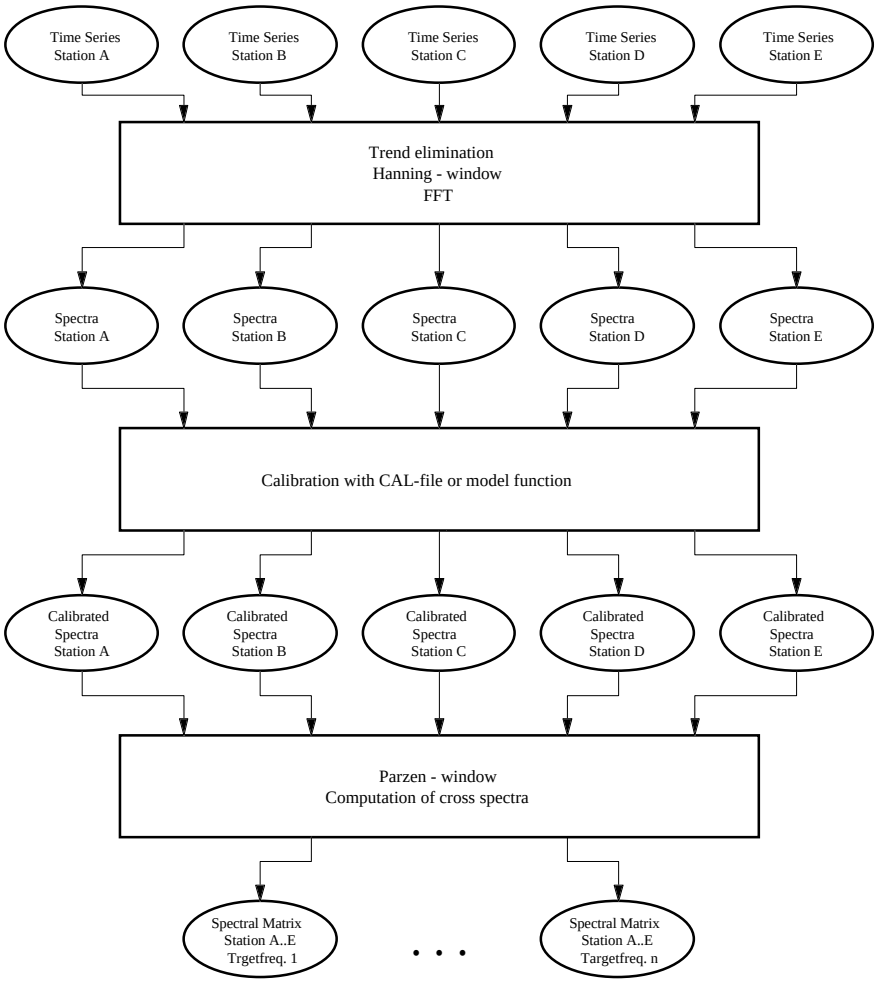


Figure 3.1: Overview about data analysis from the measured time series up to the computation of the spectral matrices

3.1.1 Transformation into Frequency Domain

This chapter describes the used algorithms and methods for time series analysis. First of all it is shown up how the raw data of the electrical and magnetical fields is transformed from time to frequency domain where the calibration of the data is performed.

Band	Blocksize	Measurement time	Sampling rate	Frequencies	Resolution
1	512	15,63 msec	32768 Hz	8192 Hz	16 sec
	1024	31,25 msec		...	32 sec
	2048	62,5 msec		256 Hz	64 sec
	4096	125,0 msec			128 sec
2	512	0,5 sec	1024 Hz	256 Hz	2 Hz
	1024	1 sec		...	1 Hz
	2048	2 sec		8 Hz	2 sec
	4096	4 sec			4 sec
3	512	16 sec	32 Hz	8 Hz	64 Hz
	1024	32 sec		...	32 Hz
	2048	64 sec		4 sec	16 Hz
	4096	128 sec			8 Hz
4	512	8:32 min	1 Hz	4 sec	2048 Hz
	1024	17:04 min		...	1024 Hz
	2048	34:08 min		128 sec	512 Hz
	4096	68:16 min			256 Hz
5	512	4 h 33 min	32 sec	128 sec	16284 Hz
	1024	9 h 06 min		...	32768 Hz
	2048	18 h 12 min		4096 sec	65536 Hz
	4096	36 h 24 min			131072 Hz

Table 3.1: Measurement times, sampling rates and resolution of the spectra in relation to the measurement range (frequency band) and to the size of the time series sections

The time series analysis is based on the sections of the measured time series. These sections can consist of 512, 1024, 2048 or 4096 data points (user selectable). Depending on the sampling rate in the specific band and the adjusted section length, different resolutions and frequency ranges are achieved. *Table 3.1* gives an overview about the corresponding values which stand in a closed relationship with the measurement systems (see also the transfer function of the instruments in *Appendix A*). The frequency range does not correspond with the range obtained

with the FFT (*Fast Fourier Transform*); moreeven it means the range which is used to fix the target frequencies.

3.1.1.1 Trend Elimination

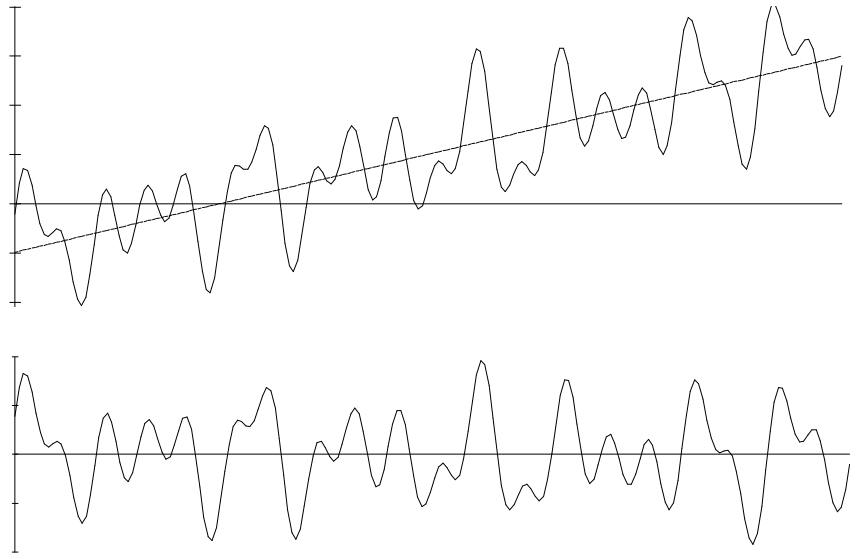


Figure 3.2: Example for trend elimination

Before applying the Fourier transformation the raw data is processed with a trend elimination and a so called window function. The trend elimination removes a possible systematic deviation from the x-axis. The mean value (*bias*) is set to zero and a straight line in the data (*trend*) which differs from the x-axis is removed. Hereby it is:

$$z_t[t] = z[t] - \underbrace{\frac{1}{t_n}\sum_{t=1}^{t_n} z[t]}_{\text{Bias}} \underbrace{- \frac{t}{t_n/2}\left(\sum_{t=1+t_n/2}^{t_n} z[t] - \sum_{t=1}^{t_n/2} z[t]\right)}_{\text{Trend}}, \qquad [3.1]$$

$$t \in [1..t_n]\ ;\ t_n \in [512,\ 1024,\ 2048,\ 4096]\ ;$$

z : time series (raw data); z_t : time series without trend.

Figure 3.2 illustrates the trend elimination. The upper figure shows an example curve superimposed by a straight line, the lower figure shows the same data set after the trend elimination.

3.1.1.2 Window Function (windowing)

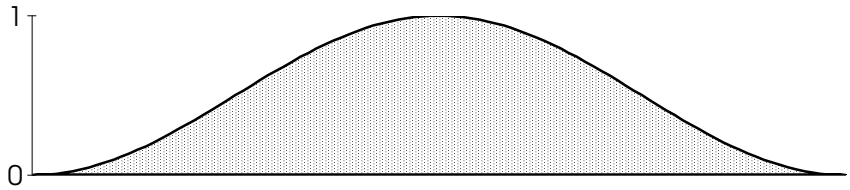


Figure 3.3: The Hanning window which is multiplied with the time series before the FFT is performed

After the trend elimination it follows the multiplication of the time series with a window function (*windowing*). This is necessary in order to suppress side effects (discontinuities are generated at the edges) at the FFT and to obtain an optimum sharp mapping of the frequency spectra. In the program a so called *Hanning window* with the function

$$Hanning(t) = \begin{cases} \frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi t}{T_0}\right) & : \quad |t| \le T_0 \\ 0 & : \quad |t| > T_0 \end{cases} \qquad [3.2]$$

has been realized.

3.1.1.3 Fast Fourier-Transformation (FFT)

After the time series has been treated with the trend elimination and the windowing the fast Fourier transformation (FFT) is applied to the data. In the program a so called mixed Radix-8 algorithm has been realized. The given time series now has been transformed into the frequency domain. All the further steps of computation are done with spectral data.

3.1.1.4 Calibration of Spectra

The measured time series data is affected by the transfer function of the instruments (*MMS03e* or *GMS05*). In order to eliminate this influence the data must be calibrated. The spectra are multiplied by the reciprocal of the transfer function of the measurement system and by this means almost ´ cleaned´ f rom influences of the instruments. Two different possibilities to determine the transfer function exist: the theoretical model function or the measured transfer function can be used. Only the

GMS05 allows the direct measurement of the calibration function. *Appendix A* describes the theoretical model functions in detail.

3.1.2 Computation of the Cross and Auto Spectra

For each target frequency the cross and auto spectra are computed from the calibrated spectra. Each of these values results from the sum of spectra over all frequency lines (Fourier-coefficients) within a window whereby in its middle the target frequency is located. In the following the computation for one frequency line is shown. This procedure is repeated for all the other target frequency lines correspondingly. In the appendix an overview about the predefined frequency lines is given (see file *PROCMT.FRQ*).

3.1.2.1 Parzen-Window

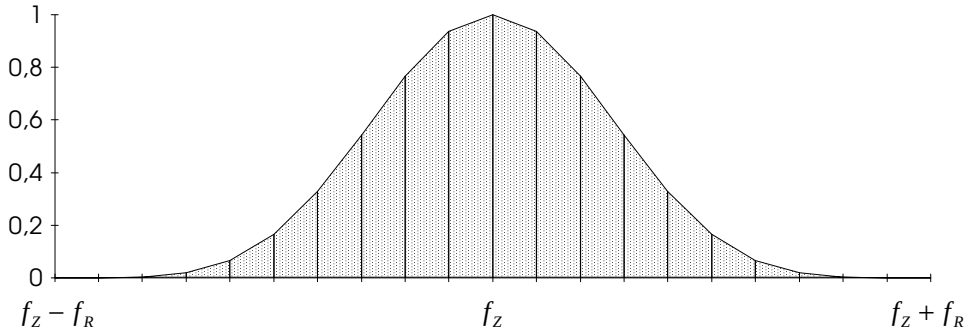


Figure 3.4: The Parzen-window over the target frequency f_Z

In order to determine the value of the cross spectra at the target frequency line not only the spectral value at the target frequency line is taken, but a window is applyed at this frequency. Here the Parzen-window is used:

$$u = \pi \; |f_Z - f| \; / f_R \qquad [3.3]$$

$$\text{parzen}(f) = \begin{cases} 1 & \text{if} \quad |f_Z - f| = 0 \\ (\sin(u)/u)^4 & \text{if} \quad 0 < |f_Z - f| < f_R \\ 0 & \text{if} \quad |f_Z - f| \geq f_R \end{cases}, \qquad [3.4]$$

with f_Z= target frequency and f_R= radial frequency. Herby the target frequency is the center frequency of the window and the radial frequency determines the width of the window. The radial frequencies are fixed depending on the target frequency:

$$f_R = f_Z \, c_R . \qquad [3.5]$$

whereby for the factor c_R a small (c_R=0,125), medium (c_R=0,25), wide (c_R=0,5) or very wide (c_R=0,75) radius can be selected.

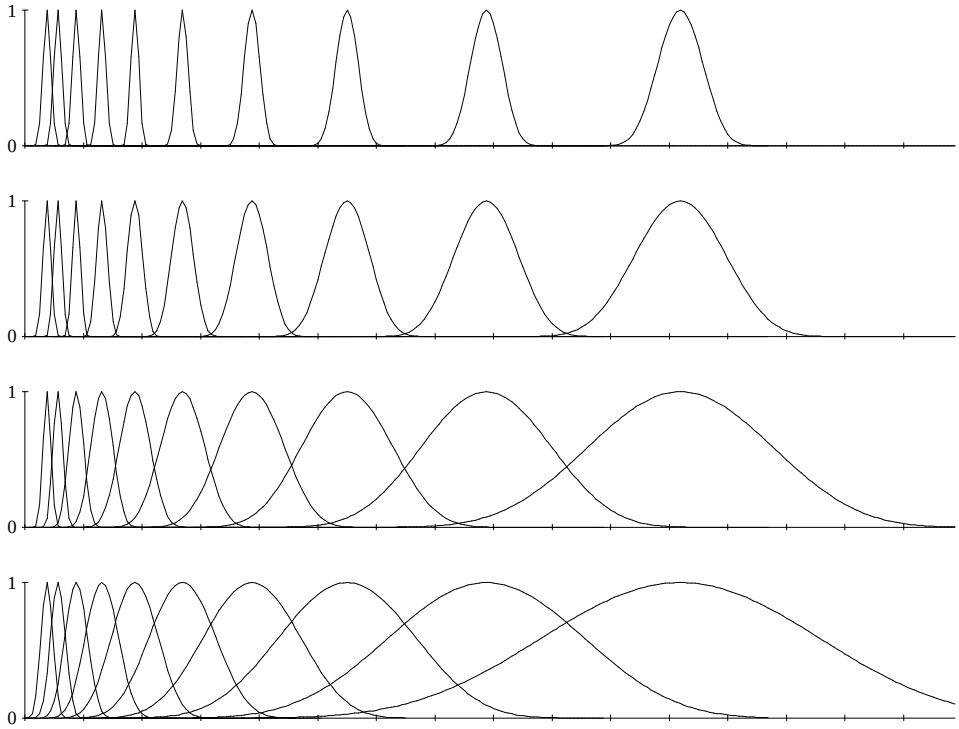


Figure 3.5: The target lines of a band with the Parzen-windows belonging to. From top to bottom: small, medium, wide, extra wide radia

Figure 3.5 gives an overview about the logarithmic equidistant target frequency lines of a band with the different adjustments for the width of the Parzen-window. The default in *PROCMT* is wide radius. An exception is band 2, where a small radius is default in order to minimize the influence of the electromagnetic noise caused by the powerlines (16⅔ Hz, 50 Hz and harmonics).

3.1.2.2 Crossing and Summing

At the cross multiplication at first two frequencies are multiplied with eachother under respect of the Parzen-window and then the sum over all frequencies is built.

$$XY^*_{f_z} = \sum_f \text{parzen}(f) \cdot X(f)\ Y(f)^* \qquad [3.6]$$

X and *Y* are the two channels, $XY^*_{f_z}$ is the cross product belonging to the frequency f_z, *X(f)* resp. *Y(f)* are complex spectral values and *parzen(f)* is the the function of the *Parzen*-window described above. In order to achieve an independence of the amplitudes of the cross and auto spectra from the width of the *Parzen*-window, equation 3.6 is expanded by a scaling factor which results from the weights of the *Parzen*-window :

$$XY^*_{f_z} = \frac{\sum_f \text{parzen}(f) \cdot X(f)\ Y(f)^*}{\sum_f \text{parzen}(f)} \quad . \qquad [3.7]$$

In the following an indexing of the cross spectra is ommited. However, it has to be considered that all the further steps of computation are performed for each target frequency independently from other target frequencies.

3.1.2.3 Degree of Freedom

The degree of freedom for the cross and auto spectra results from the number of independent values which form the single spectra. Hereby the weighting which is caused by the *Parzen*-window has to be drawn into consideration:

$$\nu = \sum_f \text{parzen}(f). \qquad [3.8]$$

By this means the degree of freedom results basically by the *Parzen*-window which determines the number of spectral values mentioning the summing and fixing the corresponding weighting.

3.1.2.4 Overlapping Sections of Time Series

Normally, the time series is split into sections succeeding to oneanother and then the data analysis is performed. It means that a part of information of the time series gets lost (see *Fig. 3.4*, upper plot). In order to minimize this loss of data, the program offers the possibility to use overlapping time segments (*Fig. 3.4*, lower plot). Also here the data analysis is performed independently to the single sections. It has to be considered nevertheless that the sections of time series are no longer independent from eachother as they partially overlap. This results in a decrease of the degree of freedom which can be determined from the size of the overlapping range.

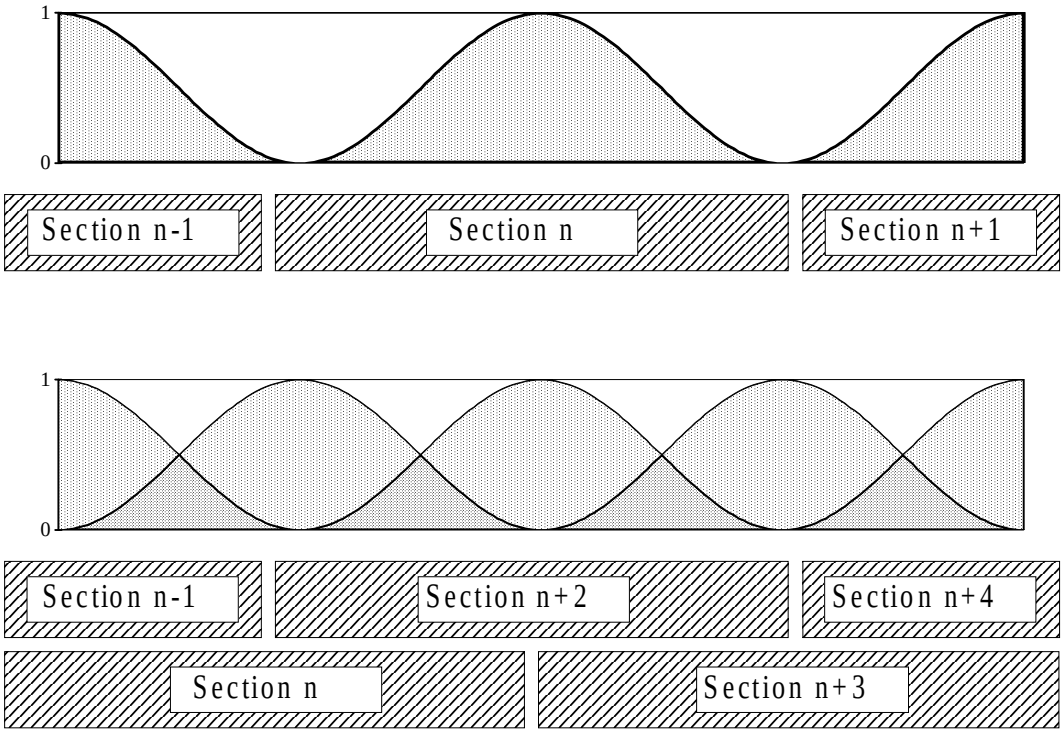


Figure 3.6: Time series with Hanning-window without (upper) and with (lower) overlapping sections

The correction factor for the degree of freedom of a section results from the overall area of the *hanning-window*

$$\begin{aligned} G_G &= \int_{-T_0}^{T_0} \frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi t}{T_0}\right) dt \\ &= \int_{-\pi}^{\pi} \frac{1}{2} + \frac{1}{2}\cos(x) dx \\ &= \pi \end{aligned} \qquad [3.9]$$

and the area of overlap with the neighbored windows

$$\begin{aligned} G_{\ddot{U}} &= 4 \cdot \int_{T_0/2}^{T_0} \frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi t}{T_0}\right) dt \\ &= 4 \cdot \int_{\pi/2}^{\pi} \frac{1}{2} + \frac{1}{2}\cos(x) dx \\ &= \pi - 2 \; . \end{aligned} \qquad [3.10]$$

The corrected degree of freedom ν' results from the full part of the non overlapping area and the half part of the overlapping area, whereby the areas are scaled with the overall area:

$$\begin{aligned} \nu' &= \nu \cdot \left(\frac{G_G - G_{\ddot{U}}}{G_G} + \frac{1}{2}\frac{G_{\ddot{U}}}{G_G} \right) \\ &= \nu \cdot \left(1 - \frac{1}{2}\frac{G_{\ddot{U}}}{G_G} \right) \\ &= \nu \cdot \left(\frac{1}{2} + \frac{1}{\pi} \right) \\ &\approx \nu \cdot 0.818 \; . \end{aligned} \qquad [3.11]$$

This degree of freedom is not valid for the first and the last section of time series. Here the area of the overlap is only half. For these two sections the degree of freedom is:

$$\begin{aligned} \nu' &= \nu \cdot \left(\frac{G_G - 1/2 * G_{\ddot{U}}}{G_G} + \frac{1}{4}\frac{G_{\ddot{U}}}{G_G} \right) \\ &= \nu \cdot \left(\frac{3}{4} + \frac{1}{2\pi} \right) \\ &\approx \nu \cdot 0.909 \; . \end{aligned} \qquad [3.12]$$

Note: The degree of freedom increases with overlapping sections of the time series whose neighbored sections have been removed by hand selection (see *chapter 1.3.4*) corresponding to equation 3.12. A correction of the degree of freedom is not done in this special case.

3.2 Stacking Algorithms and Robust Methods

The cross and auto spectra can be written in form of a square matrix. The length of the matrices edges corresponds with the number of channels recorded. This matrix with the cross and auto spectra is meant when in the further chapters is spoken about the spectral matrix **S**.

This chapter describes the methods to determine an optimum matrix for each target frequency. It is the task to compute a single matrix from all matrices (up to several hundred) which is achieved with statistical methods. Two basically different methods are used here: the selective stacking and the stacking of weights. Before stacking, the matrices are scaled in order to avoid that extremely differing amplitudes of the natural stimulation influence the result of stacking.

3.2.1 Coherency

The coherency between two channels is a quantity describing the linear dependence between these channels:

$$\mathrm{coh}(A,B) = \frac{AB^*}{\left(AA^*\ BB^*\right)^{1/2}}\ . \qquad [3.13]$$

This coherency term can also be used to compare the measurement result of a channel with a predicted result of the same channel (*predicted channel)*. In this case it is called *multiple* coherency. It is :

$$\mathrm{coh}(Z,\hat{Z}) = \frac{Z\hat{Z}^*}{\left(ZZ^*\ \hat{Z}\hat{Z}^*\right)^{1/2}} \qquad [3.14]$$

with

$$\begin{aligned} \hat{Z} &= a\,X + b\,Y\ , \\ \hat{Z}Z^* &= a\,XZ^* + b\,YZ^*\ , \\ \hat{Z}\hat{Z}^* &= a\,X\hat{Z}^* + b\,Y\hat{Z}^*\ . \end{aligned} \qquad [3.15]$$

For *a* and *b* it is:

$$a = \frac{ZX^*\,YY^* - YX^*\,ZY^*}{XX^*\,YY^* - XY^*\,YX^*} \qquad [3.16]$$

$$b = \frac{ZY^*\,XX^* - XY^*\,ZX^*}{XX^*\,YY^* - XY^*\,YX^*} \qquad [3.17]$$

$$\text{with} \quad XX^*, XY^*, YY^*, ZY^*, ZX^* \in \mathbf{S}\ .$$

The coherency between one channel and the predicted result delivers a value for the quality of the measurement and by this means for the spectral matrix **S** computed from the time series. As several equations can be defined with the matrix (for the standard MT-method these are for instance $E_x = a_1 H_x + b_1 H_y$ and $E_y = a_2 H_x + b_2 H_y$), the term of the coherency of a spectral matrix is defined as follows:

$$\mathrm{coh}(\mathbf{S}) = \min_k\left(\left|\mathrm{coh}(Z_k, \hat{Z}_k)\right|\right), \qquad [3.18]$$

with $k \in [1, m]$; *m*: number of defined equations and the equations itself

$$Z_k: \quad Z_k = a_k X_k + b_k Y_k\ . \qquad [3.19]$$

When in the following chapters the coherency is mentioned then mostly the coherency of a spectral matrix is meant.

Especially for the Q- and W- algorithm (Junge [90]) an additional coherency term has to be defined, the so called global coherency:

$$\mathrm{coh}(Z, \hat{\bar{Z}}) = \frac{Z\hat{\bar{Z}}^*}{\left(ZZ^*\ \hat{\bar{Z}}\hat{\bar{Z}}^*\right)^{1/2}} \qquad [3.20]$$

with

$$\begin{aligned} \hat{\bar{Z}} &= \bar{a}X + \bar{b}Y \,, \\ \hat{\bar{Z}}Z^* &= \bar{a}XZ^* + \bar{b}YZ^* \,, \\ \hat{\bar{Z}}\hat{\bar{Z}}^* &= \bar{a}X\hat{\bar{Z}}^* + \bar{b}Y\hat{\bar{Z}}^* \,. \end{aligned} \qquad [3.21]$$

Hereby it is $\bar{a}$ and $\bar{b}$

$$\bar{a} = \frac{\overline{ZX}^*\,\overline{Y}\,\overline{Y}^* - \overline{Y}\,\overline{X}^*\,\overline{ZY}^*}{\overline{XX}^*\,\overline{Y}\,\overline{Y}^* - \overline{XY}^*\,\overline{YX}^*} \qquad [3.22]$$

and

$$\bar{b} = \frac{\overline{ZY}^*\,\overline{XX}^* - \overline{XY}^*\,\overline{ZX}^*}{\overline{XX}^*\,\overline{Y}\,\overline{Y}^* - \overline{XY}^*\,\overline{YX}^*} \qquad [3.23]$$

with

$$\overline{XX}^*\,, \overline{XY}^*\,,\ \overline{Y}\,\overline{Y}^*,\ \overline{ZY}^*,\ \overline{ZX}^* \in \overline{\mathbf{S}}\,.$$

In order to point out the difference of the two coherency terms, $\mathrm{coh}(Z,\hat{Z})$ is called local coherency as it only refers to one single matrix. The essential difference between the global and the local coherency is the computation of equation parameters *a* and *b* resp. $\bar{a}$ and $\bar{b}$. At the global coherency the parameters are computed from the matrix $\overline{\mathrm{S}}$ which is a result of stacking of all matrices $\mathrm{S_i}$ (see equations 3.20 to 3.23). At the local coherency the parameters are computed from the matrix $\mathrm{S_i}$ for which also the coherency is calculated (equations 3.14 to 3.17).

3.2.2 Scaling of the Spectral Matrices

The measured electromagnetic fields strongly vary in their amplitude. The searched transfer functions are not affected by this. As they result as quotients of electromagnetic fields the part of the amplitude is reduced in denominator and numerator. However, this is not valid for the cross and auto spectra of the spectral matrix. In contrary, by means of the multiplication of two measurement channels the influence of the amplitude is amplified even. These strongly varying amplitudes of the cross and auto spectra would influence the weighted stacking.

Another motivation to implement a scaling is the following consideration: It can be assumed that just some of the strongly distorted matrices have an especially strong stimulation, i.e. the distortion amplitude. This would have the effect that just the distorted matrices would have a high influence to the result of the stacking.

Due to the above reasons the matrices are scaled and released from the influence of distortions:

$$\mathbf{S}_i' = \frac{1}{\mathrm{spur}(\mathbf{S}_i)}\,\mathbf{S}_i \qquad [3.24]$$

As all cross and auto spectra are divided by the same value the result of the transfer function is not changed, as they are computed by the quotient of the fields:

$$\overline{\mathbf{S}}' = \overline{\mathbf{S}}\;\frac{1}{n}\sum_{i=1}^{n}\mathrm{spur}(\mathbf{S}_i)\;. \qquad [3.25]$$

By this means the spectral matrix contains cross and auto spectra whose amplitude corresponds to the mean measured amplitude.

3.2.3 Short Introduction into the Robust methods (Outlier Problem)

When determining the optimum matrix it is assumed that all spectral matrices S_i are combined by the searched optimum (error free) matrix S_O and an unknown error matrix ΔS_i

$$\mathbf{S}_i = \mathbf{S}_O + \Delta\mathbf{S}_i \qquad [3.26]$$

In case that the error matrices have a symmetrical distribution, an approximation to the desired optimum matrix can be achieved just by simple stacking of many matrices:

$$\frac{1}{n}\sum_i \mathbf{S}_i = \mathbf{S}_O + \frac{1}{n}\sum_i \Delta\mathbf{S}_i \qquad [3.27]$$

$$\lim_{n\to\infty} \frac{1}{n}\sum_{i=1}^{n}\mathbf{S}_i = \mathbf{S}_O \ . \qquad [3.28]$$

For sufficient high *n* it is:

$$\overline{\mathbf{S}} \ = \ \mathbf{S}_O + \frac{\mathbf{1}}{n}\sum_{i=1}^{n}\Delta\mathbf{S}_i \ \approx \ \mathbf{S}_O \ . \qquad [3.29]$$

Often the measurement results are affected by strong noise which does not obey the hypothesis of a symmetrical distribution:

$$\lim_{n\to\infty} \frac{1}{n}\sum_{i=1}^{n}\Delta\mathbf{S}_i \neq 0. \qquad [3.30]$$

Another problem of these strongly distorted matrices is that they mostly have too big deviations from the searched value. This leads to the phenomena that even a few strongly distorted matrices are sufficient to effect a considerable deviation from the true result, the optimum matrix.

3.2.4 Selective Methods

The selective methods try to minimize the outlier problem by excluding a number of matrices from taking the average. The problem on one hand is to select a maximum number of matrices and on the other hand to exclude almost all outliers from averaging.

3.2.4.1 Simple Stacking

$$\overline{\mathbf{S}} = \frac{1}{n}\sum_{i}\mathbf{S}_{\mathrm{i}} \quad \text{mit} \quad i \in [1..n] \qquad [3.31]$$

This method is only mentioned for completeness. It is no robust method.

3.2.4.2 Selection with Coherency Threshold

This method uses the coherency (see *chapter 3.2.1*) to separate the outliers from the rest of matrices. Hereby only those matrices are taken for averaging whose coherency exceeds a certain threshold:

$$p(\mathbf{S}) = \begin{cases} 1 \text{ wenn } |\text{coh}(\mathbf{S})| \geq c_s \\ 0 \text{ wenn } |\text{coh}(\mathbf{S})| < c_s \end{cases} \qquad [3.32]$$

with c_S: coherency threshold. For the stacked matrix it is:

$$\overline{\mathbf{S}} = \frac{\mathbf{1}}{\sum_i p(\mathbf{S_i})} \sum_i p(\mathbf{S_i})\, \mathbf{S_i} \ . \qquad [3.33]$$

It is important to fix the threshold c_S properly. If it is too small, some strongly distorted matrices are included. When it is too big only a few and perhaps even no matices at all are selected. Additionally, the coherency distribution varies from target frequency to target frequency considerably. Due to that reason for each measurement and for all target frequencies different thresholds have to be fixed in order to obtain optimum results.

Note: With the menu **Estimate SPM.Coh Threshold** this method of stacking can be selected. Whereby the coherency factors c_S will be determent by the factors which are displayed at the right lower edge of the main window.

3.2.4.3 Selection by Adaptive Coherency Threshold

Mathematically this method can be described as a simple coherency threshold method (3.32, 3.33) with the following iteration algorithm to determine the threshold c_S:

$$\begin{aligned} c_s^{(0)} &= 1.0 \\ c_s^{(j)} &= c_s^{(j-1)} - 0.01 \ . \end{aligned} \qquad [3.34]$$

The iteration stops as soon as :

$$\frac{\sum_{i=1}^{n} \mathrm{p}(\mathbf{S_i})}{n} \geq f_b \qquad [3.35]$$

with $i \in [1,n]$, $c_s = c_s^{(j)}$ and f_b: factor of band b. In order to avoid the disadvantages of the coherency threshold method not the coherency threshold itself is set but a number of matrices which shall be selected. Here the matrices with the lowest coherencies are excluded from averaging. In case a factor $f_b = 0.9$ is selected and we have 200 matrices in total then 180 matrices will be selected. All those with a higher coherency will be selected. As the noise differs from band to band (normally band 3 has the highest noise and the lowest signal) a different factor can be defined for each band.

Note: With the menu **Estimate SPM.Coherency** this method of stacking can be selected. Whereby the coherency factors f_b will be determent by the factors which are displayed at the right lower edge of the main window.

3.2.4.4 Adaptive Selection Method Respecting a Mean Coherency

This method is another conjugation of the coherency threshold method and is oriented to the selection method mentioned above. The difference is that the number of the matrices to be selected is not determined by the user, the program computes this factor for each target line. In order to determine the number of matrices to be selected first of all the mean coherency of all matrices is computed. Then the part of the matrices to be selected is determined according to the formula:

$$f = \frac{1}{n} \sum_i \mathrm{coh}(\mathbf{S}_i) \qquad [3.36]$$

The idea is here that the number of the strongly distorted matrices is the bigger, the smaller the mean coherency becomes.

It has to be respected that the computed factor corresponds with the average coherency. However, the factor f is no coherency threshold, but represents the number of the matrices to be respected in averaging. This means when the mean coherency threshold is 0.6, 60% of all matrices will be included in averaging.

Mainly this algorithm corresponds to the algorithm with selection by adaptive coherency threshold where the factor f_b in equation 3.35 is replaced by *f*.

3.2.4.5 Degree of Freedom for the Selective Methods

For all shown selective methods the degree of freedom of the computed matrix $\overline{S}$ results from the following equation:

$$\overline{v} = \sum_i \mathrm{p}(\mathbf{S}_i)\ v_i\ . \qquad [3.37]$$

As is $v_i = v_j$ for all $i, j \in [1..n]$ it results

$$\overline{v} = v \sum_i \mathrm{p}(\mathbf{S}_i)\ . \qquad [3.38]$$

The simple stacking can be considered as a stacking with the coherency threshold 0.0. The equation standing above is valid correspondingly.

expected value

3.2.5 Stacking with Weights (Robust Methods)

Another possibility to counteract the outlier problem (ref. *chapter 3.2.3*) are robust methods. A statistical method is called robust when it is not sensitive against outliers. It means that some, few outliers do not or only little influence the estimation of the expected value of a probability distributaion.

3.2.5.1 MF-Method (fitting according to the most frequent value)

This method was developed by STEINER [80a, 80b]. It is a robust method with a weighting function which tries to give the highest weight to the most frequent values. Less frequent values with bigger deviation from the average get less and less meaning from iteration step to iteration step. By this means a better and better adaption of the average to the most frequent values is achieved:

$$M = \frac{\int_{-\infty}^{+\infty} xG(x) f(x)dx}{\int_{-\infty}^{+\infty} G(x) f(x)dx} \qquad [3.39]$$

$$G(x) = \frac{1}{\varepsilon^2 + (x - M)^2} \qquad [3.40]$$

The estimated value is expanded in a way that the probality density *f(x)* is multiplied by a weighting function *G(x)*. The shape of the weighting function for differnt ε can be found in *figure 3.7*

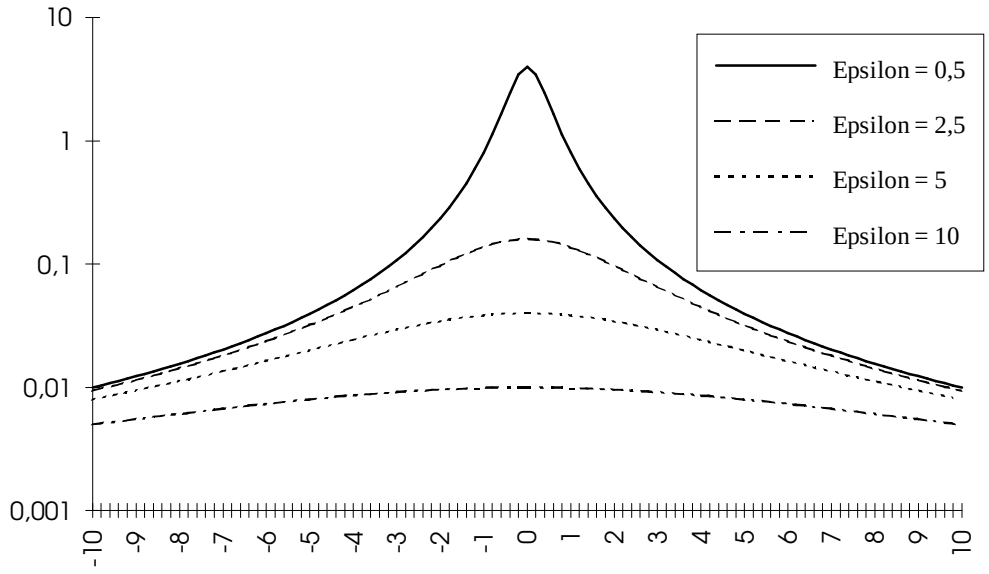


Figure 3.7: Weighting function $G_\varepsilon(x)$ with x-Axis (x-M): Distance from

As *M* is defined recursively its value is computed iteratively. The optimum value for the parameter ε results by the following stipulation:

$$F(\varepsilon) = \varepsilon^3 \left(\int_{-\infty}^{+\infty} G(x) f(x)dx \right)^2 = \max. \qquad [3.41]$$

Figure 3.8 shows the shape of the function *f(ε)* for different example data.

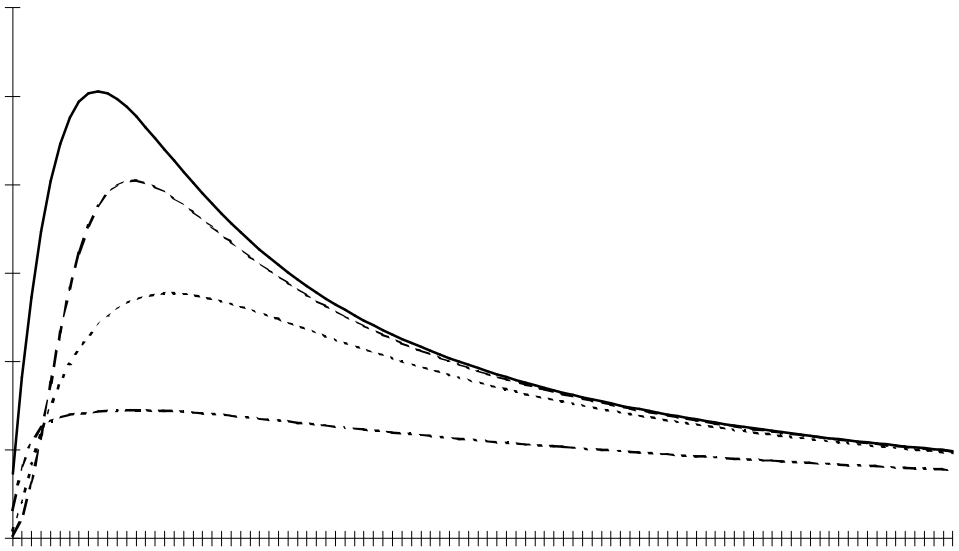


Figure 3.8: F(ε) with four example data sets. For the searched ε is: F(ε) = Maximum

With the following equations the transfer from the continuous to the discrete range is accomplished:

$$\overline{x}^{(j)} = \frac{\sum_{i=1}^{n} g_i^{(j)} x_i}{\sum_{i=1}^{n} g_i^{(j)}} \qquad [3.42]$$

$$g_i^{(j)} = \frac{1}{\varepsilon^{(j)^2} + d_i^{(j-1)^2}} \qquad [3.43]$$

For $\varepsilon^{(j)}$ i.e. correspondingly:

$$\begin{aligned} F(\varepsilon^{(j)}) &= \varepsilon^{(j)^3} \left(\sum_{i=1}^{n} g_i^{(j)} \right)^2 \\ &= \varepsilon^{(j)^3} \left(\sum_{i=1}^{n} \frac{1}{\varepsilon^{(j)^2} + d_i^{(j-1)^2}} \right)^2 \\ &= \text{Maximum} \end{aligned} \qquad [3.44]$$

The distances result from

$$d_i^{(j)} = x_i - \overline{x}^{(j)}. \qquad [3.45]$$

It stays to clarify the problem how to fix the start values for iteration 0. For $\overline{X}^{(0)}$ the simple average or median can be taken:

$$\overline{x}^{(0)} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad [3.46]$$

or

$$\overline{x}^{(0)} = \underset{i}{\text{Median}}(x_i). \qquad [3.47]$$

In order to determine the maximum of the function *F(ε)* a simple arrangement can be used :

$$\begin{aligned} \varepsilon_{(0)}^{(j)} &= \varepsilon^{(j-1)} \\ &\text{bzw. für } j = 1\text{:} \\ \varepsilon_{(0)}^{(1)} &= \max(x_i) - \min(x_i) \\ \varepsilon_{(k)}^{(j)} &= \varepsilon_{(k-1)}^{(j)}\, c\,; \qquad c \in [0{,}9..1) \end{aligned} \qquad [3.48]$$

The iteration stops when :

$$F(\varepsilon_{(k)}^{(j)}) < F(\varepsilon_{(k-1)}^{(j)}) \qquad [3.49]$$

The searched ε is then:

$$\varepsilon^{(j)} = \varepsilon_{(k-1)}^{(j)} \qquad [3.50]$$

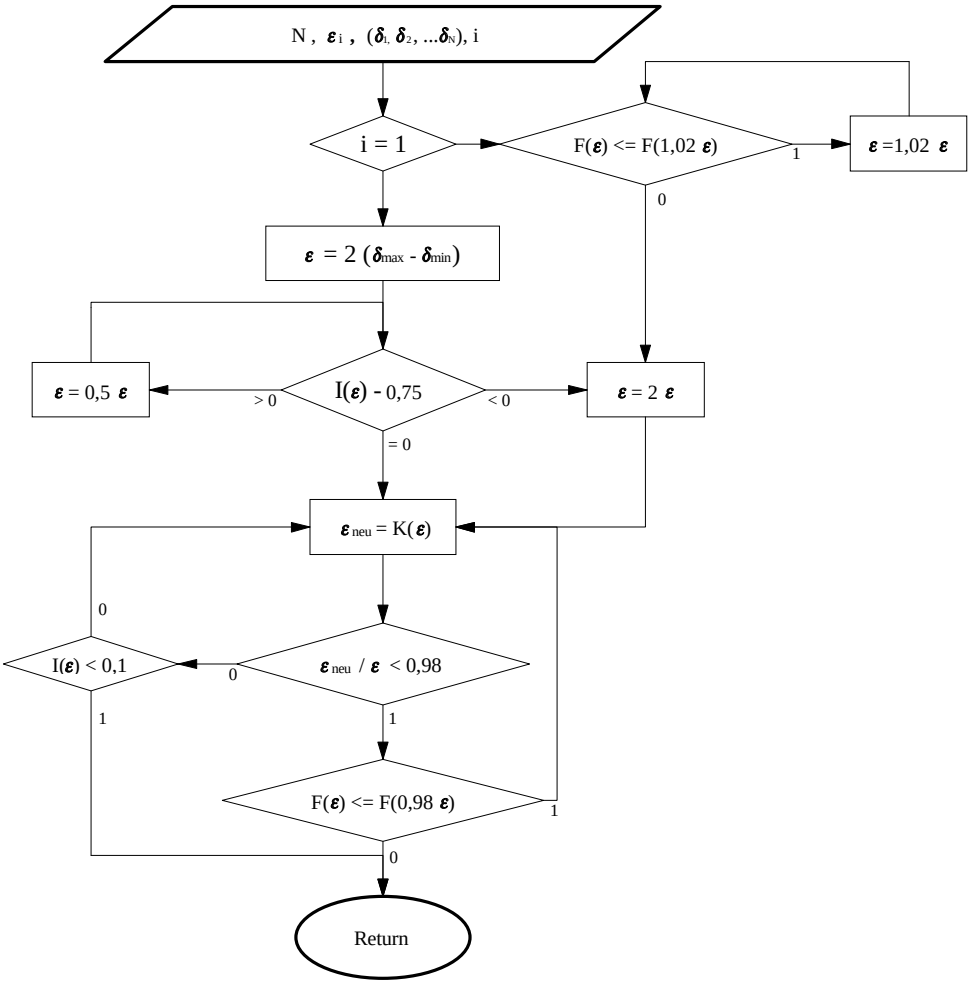


Figure 3.8: Flow chart of the algorithm to determine ε according to HAJAGOS [80]

An efficient algorithm to determine ε is proposed by HAJAGOS [80]. *Figure 3.9* shows the method in a flow chart.

3.2.5.2 Weighted Average of the Transfer Function

In contrast to all other methods here the coherencies are not used. It is assumed that a distortion will influence the computed transfer function and cause a deviation (outlier). Therefore at first a weighted average of the transfer functions is computed and after that (with the same weights) a weighted average of the spectral matrices.

At first a simple average is computed from all transfer functions:

$$\bar{a}_k^{(0)} = \sum_{i=1}^{n} a_{i,k} \qquad [3.51]$$

$$\bar{b}_k^{(0)} = \sum_{i=1}^{n} b_{i,k} \qquad [3.52]$$

$$a_{i,k} = \frac{ZX^*_{i,k}\ YY^*_{i,k} - YX^*_{i,k}\ ZY^*_{i,k}}{XX^*_{i,k}\ YY^*_{i,k} - XY^*_{i,k}\ YX^*_{i,k}} \qquad [3.53]$$

$$b_{i,k} = \frac{ZY^*_{i,k}\ XX^*_{i,k} - XY^*_{i,k}\ ZX^*_{i,k}}{XX^*_{i,k}\ YY^*_{i,k} - XY^*_{i,k}\ YX^*_{i,k}} \qquad [3.54]$$

with $XX^*_{i,k}\ ,\ XY^*_{i,k}\ ,\ YY^*_{i,k},\ ZY^*_{i,k},\ ZX^*_{i,k}\ \in\ \mathbf{S}_i$

$k \in [1..m]$; m: number of equations

$i \in [1..n]$; n: number of matrixes

These transfer functions are used as start values for the iteration according to the MF-method in order to determine a weighted average of all transfer functions. Hereby the entered equations are not computed independently but all together. The distance is defined as:

$$d_i^{(j)} = \left(\sum_{k=1}^{m} \left(a_{i,k} - \bar{a}_k^{(j)} \right)^2 + \left(b_{i,k} - \bar{b}_k^{(j)} \right)^2 \right)^{1/2} \qquad [3.55]$$

As the distance definition delivers positive values only, the start initialisation of ε is modified correspondingly (see *chapter 3.2.5.1*). It is now

$$\varepsilon^{(0)} = 2\ \max_i(d_i^{(0)}). \qquad [3.56]$$

For the iterative computation is:

$$\varepsilon^{(j)} = F(\varepsilon^{(j-1)}, d_1^{(j-1)}, d_2^{(j-1)}, \cdots, d_n^{(j-1)}) \qquad [3.57]$$

$$g_i^{(j)} = \frac{1}{\varepsilon^{(j)^2} + d_i^{(j)^2}} \qquad [3.58]$$

$$\bar{a}_k^{(j)} = \frac{1}{\sum_{i=1}^{n} g_i^{(j)}} \sum_{i=1}^{n} g_i^{(j)}\ a_{i,k} \qquad [3.59]$$

$$\bar{b}_k^{(j)} = \frac{1}{\sum_{i=1}^{n} g_i^{(j)}} \sum_{i=1}^{n} g_i^{(j)}\ b_{i,k} \qquad [3.60]$$

The iteration is stopped when the parameter for the weighting function does not change any more or only changes very little:

$$\frac{\varepsilon^{(j)}}{\varepsilon^{(j-1)}} \geq \Delta\varepsilon \quad \text{mit} \quad \Delta\varepsilon = 0,99 \qquad [3.61]$$

$$\bar{\mathbf{S}} = \frac{1}{\sum_{i=1}^{n} g_i^{(j)}} \sum_{i=1}^{n} g_i^{(j)} \mathbf{S}_i \qquad [3.62]$$

The degree of freedom results in:

$$\bar{\nu} = \nu \sum_{i=1}^{n} g_i^{(j)}\ . \qquad [3.63]$$

Appendix A

Transfer Functions of

GMS05 and *MMS03e*

A.1. Transfer Function of *MMS03e*

A.1.1 Magnetometer KIM 877M

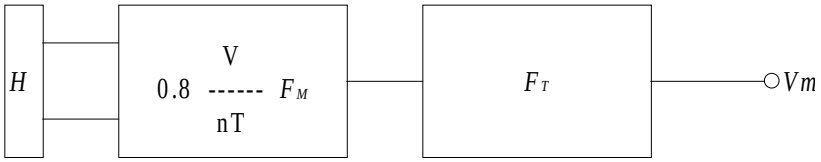


Figure A.1.1: diagram of the transfer function of the KIM 877M

The *Metronix* Magnetometer KIM 877M is an induction coil magnetometer operating with feedback principle. The feedback loop is closed for frequencies higher than 4 Hz. *Figure A.1.1* explains the transfer function of this sensor.

The following formula gives a mathematical description between the magnetic field H and the sensor output voltage V_M :

$$\mathrm{V_M} = \frac{j \cdot f \cdot E_0}{1 + j \cdot \frac{f}{4\,\mathrm{Hz}}} \cdot H = E_0 \cdot 4\,\mathrm{Hz} \cdot F_M \cdot H \cdot F_T \quad \text{mit} \quad E_0 = 0.2\,\frac{\mathrm{V}}{\mathrm{nt} \cdot \mathrm{Hz}}.$$

E_0 is the calibrated sensitivity of the sensor and it is:

$$F_M = \frac{P}{1+P} \quad \text{with} \quad P = j \cdot \frac{f}{4\,\mathrm{Hz}}$$

and

$$F_T = \frac{1}{1+P_T} \quad \text{with} \quad P_T = j \cdot \frac{f}{1591\ \mathrm{Hz}}\ .$$

A.1.2 Transfer Function of the Electric Fields

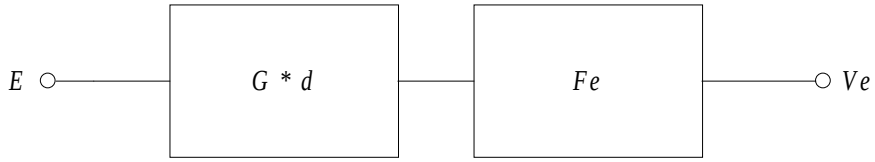


Figure A.1.2: diagram of the transfer function of an electric field sensor

The *Metronix* E-field device includes a built-in preamplifier for amplification of the very weak sensor signals coming from the electric field probes. *Figure A.1.2* explains the transfer function of the electric field sensor. The electrical field is determined by the voltage difference between the two electrodes which have contact with the soil and are located from each other with the probe distance *d*.

$$V_E = G_E \cdot d \cdot E \cdot \frac{1}{1+P_E} \quad \text{with} \quad P_E = j \cdot \frac{f}{1591\ \text{Hz}} \quad \text{and} \quad G_E = 30$$

$$F_E = \frac{1}{1+P_5}$$

Here E is the measured electrical field and V_e the output voltage between the sensors. G_e is the amplification and d the probe distance.

A.1.3 Overview about SCU 884

The SCU 884 (Signal Conditioning Unit) from *Metronix* is used for amplification and filtering of up to 8 analog channels in a frequency range from DC to 256 Hz. The hardware is the same for each of the channels. Due to the high dynamic range of the input signals and for data reduction at lower frequencies this wide frequency range is split into 4 bands with three different sample frequencies. In the lowest frequency band a digital filter for data reduction during recording is implemented.

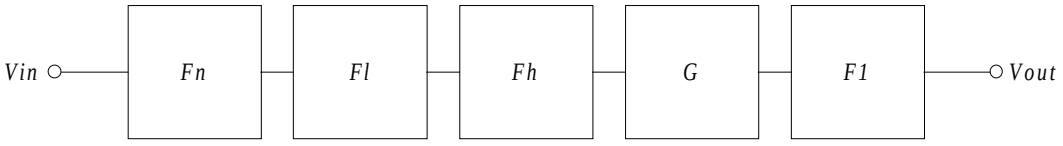


Figure A.1.3: Block diagram of the transfer function of the SCU 884 channels

The *table A.1.1* shows the filter settings of the bands and the sampling rates. *Table A.1.2* shows an overview about the frequency ranges of the bands.

NOTE: Normally, the bands are numbered with 1 to 4 in the *MMS03E* documentation. In order to keep the numbering consistently (same band numbers for *MMS03e* and *GMS05*) the enumeration starts with band 2 here.

Band	High-pass	Low-pass	Sampling rate
2	4 Sec	265 Hz	1024 Hz
3	4 Sec	8 Hz	32 Hz
4	4096 Sec	4 Sec	1 Hz
5	DC / 4096 Sec	4 Sec	(dig. filtered) 1 Hz

Table A.1.1: Filter frequencies and sampling rates

Band 2	8 Hz	256 Hz
Band 3	4 Sec	8 Hz
Band 4	128 Sec	4 Sec
Band 5	DC / 4096 Sec	128 Sec

Table A.1.2: Cut-off frequencies and frequency bands

The gain of each channel can be adjusted separately. Possible gain settings are x1, x3, x10, x30 , x100, x300. Further on, there are up to 4 notch filters for suppression of cultural noise caused by power lines. The setting of a notch filter as well as the band and high-pass settings always influence all connected SCU channels simultaneously. The next sections describe the transfer functions of these filters in detail.

A.1.4 Notch Filters of the SCU 884

The following equation describes the notch filter transfer function.

$$F_N = \frac{1}{1 + \frac{1}{Q} \cdot \sum_{v=1}^{4} S_V \cdot \frac{P_V}{1 + P_V^2}} \quad \text{with} \quad Q = 5 \quad \text{and} \quad P_V = j \cdot \frac{f}{f_{N,V}}$$

Q defines the quality of the notch filter. $f_{N,v}$ is the center frequency of the selected notch and S_v is a factor depending on the notch v being switched on or off.. If Notch v is not switched on, than S_v=1 else S_v=0.

Up to four of the flowing frequencies can be realized: 16.66 Hz, 50 Hz, 60 Hz, 100 Hz, 120 Hz, 150 Hz, 180 Hz, 200 Hz, 240 Hz, 250 Hz and 300 Hz.

Note: As the files of the time series recording do not contain the notch frequencies but the status of the notches only, *PROCMT* assumes that the order of the notches is as follows: notch 1 ≡ 50 Hz, notch 2 ≡ 150 Hz, notch 3 ≡ 16.667 Hz. Otherwise *PROCMT* will not operate properly with *MMS03E* data. This mainly refers to band 2. The error can be neglected for all other frequency bands.

The Low-pass filters are switched according to the selected band. The corresponding frequencies can be seen in *table B.1*. The filters are implemented as 5-pole *Butterworth low-pass* filters and have the following transfer function:

$$F_L = \frac{1}{1+P} \times \frac{1}{1 + a_1 \times P_L + P_L^2} \times \frac{1}{1 + a_2 \times P_L + P_L^2} \quad \text{mit} \quad \begin{matrix} a_1 = 1.618 \\ a_2 = 0.618 \end{matrix}$$

with P_L:

$$P_L = \begin{cases} 0 & \text{in Band 2} \\ j \cdot \frac{f}{8\,\text{Hz}} & \text{in Band 3} \\ j \cdot f \cdot 4\ \text{Hz} & \text{in Band 4 or Band 5} \end{cases}$$

A.1.5 High-pass Filters of the SCU 884

The SCU contains a switchable 1-pole high-pass filter with a cut-off frequency which depends on the selected band and the position of the *HP/DC switch* (see *table B.1*). If the high-pass is switched off it is

$$F_H = 1$$

else it is

$$F_H = \frac{P_H}{1 + P_H} \quad \text{with} \quad \begin{array}{ll} P_H = j \cdot f \cdot 4 \text{ Sec.} & \text{in Band 2 and 3} \\ P_H = j \cdot f \cdot 4096 \text{ Sec.} & \text{in Band 4 and 5} \end{array}$$

A.1.6 256 Hz Low-pass Filter of the SCU 884

The last stage of the SCU-electronics is a five pole 256 Hz *Butterworth* low-pass filter with the following transfer function:

$$F_1 = \frac{1}{1 + P_1} \times \frac{1}{1 + a_1 \times P_1 + P_1^2} \times \frac{1}{1 + a_2 \times P_1 + P_1^2}$$

$$\text{with} \quad a_1 = 1.618\,, \quad a_2 = 0.618\,, \quad P_1 = j \times \frac{f}{256\text{Hz}}$$

A.1.7 Overall Transfer Function of the E- and H-channel

The transfer functions of sensors and SCU electronics can be combined as follows:

$$\frac{V_E}{E} = F^E = G_E \cdot F_N \cdot F_L \cdot F_H \cdot G \cdot F_1 \cdot F_S \cdot d \cdot F_E$$

for the electric field channels and

$$\frac{V_H}{H} = F^H = 0.8 \text{ V / nT} \cdot F_N \cdot F_L \cdot F_H \cdot G \cdot F_1 \cdot F_T \cdot F_M$$

for the magnetic field channels.

A.1.8 Analog / Digital Converter of the SCU

The A/D converter has a resolution of 16 Bit with a maximum input voltage of :

$$V_{inMax} = \pm\ 10\ \text{V}$$

This results in a resolution of

$$V_{LSB} = {}^{10\,\text{V}}\!/_{2^{15}} = 305.2\,\mu\text{V}$$

per Bit.

Due to the influence of the round robin scheme of the ADC the channels are effected by a phase shift. This phase offset depends on the frequency band and the channel number. The phase offset for the highest frequency (HFreq) of a channel in respect to the first channel are:

Band	2	3 / 4	5
channel 1	$\Delta\varphi=0°$	$\Delta\varphi=0°$	$\Delta\varphi=0°$
channel 2	$\Delta\varphi=10°$	$\Delta\varphi=0.3125°$	$\Delta\varphi<1°$
channel 3	$\Delta\varphi=20°$	$\Delta\varphi=0.625°$	$\Delta\varphi<1°$
channel 4	$\Delta\varphi=30°$	$\Delta\varphi=0.9375°$	$\Delta\varphi<1°$
channel 5	$\Delta\varphi=40°$	$\Delta\varphi=1.25°$	$\Delta\varphi<1°$
channel 6	$\Delta\varphi=50°$	$\Delta\varphi=1.5625°$	$\Delta\varphi<1°$
channel 7	$\Delta\varphi=60°$	$\Delta\varphi=1.875°$	$\Delta\varphi<1°$
channel 8	$\Delta\varphi=70°$	$\Delta\varphi=2.1875°$	$\Delta\varphi<1°$

The highest frequencies of the bands are:

Band	2	3	4
HFreq	256 Hz	8 Hz	0.25 Hz

The phase offset for other frequencies than the highest frequency of a band is:

$\Delta\varphi_f=\Delta\varphi*(\text{frequency}/\text{HFreq[band]})$.

A.2. Transfer Function of *GMS05*

A.2.1. Electric Field Sensor with Preamplifier (EPR05)

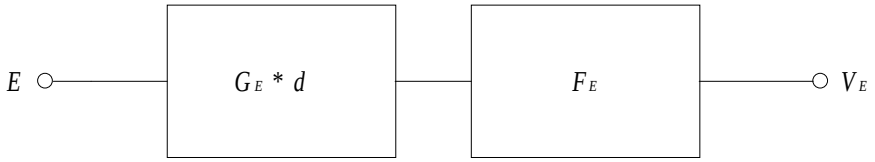


Figure A.2.1: blockdiagram of transfer function of an electric field sensor

The *Metronix* E-field device includes a built-in preamplifier for amplification of the very weak sensor signals coming from the electric field probes. *Figure A.2.1* explains the transfer function of the electric field sensor. The electrical field is determined by the voltage difference between the two electrodes which have contact with the soil and are located from each other with the probe distance *d*.

$$V_E = d \cdot E \cdot (1 + \frac{G_E}{1 + P_5}) \quad \text{with} \quad P_5 = j \cdot \frac{f}{8174\ \text{Hz}} \quad \text{and} \quad G_E = 28.64$$

$$F_E = 1 + 28.64 \cdot \frac{1}{1 + P_5}$$

Here E is the measured electrical field and V_e the output voltage between the sensors. G_e is the amplification and d the probe distance.

A.2.2. Magnetic Field Sensor (MFS05)

The *Metronix* Magnetometer *MFS05* is an induction coil magnetometer operating with the feedback principle. The feedback loop is closed for frequencies higher than 4 Hz. *Figure A.2.2* explaines the transfer function of this sensor.

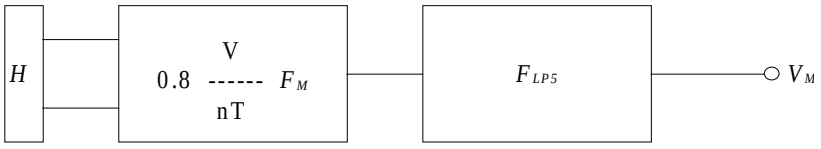


Figure A.2.2: Blockdiagram of the transfer function of the MFS05

The following formula gives a mathematical description between the magnetic field H and the sensor output voltage V_M :

$$\mathrm{V_M} = \frac{j \cdot f \cdot E_0}{1 + j \cdot \frac{f}{4\,\mathrm{Hz}}} \cdot H = E_0 \cdot 4\,\mathrm{Hz} \cdot F_M \cdot H \cdot F_{LP5} \quad \text{with} \quad E_0 = 0.2 \frac{\mathrm{V}}{\mathrm{nT} \cdot \mathrm{Hz}}.$$

E_0 is the calibrated sensitivity of the sensor and it is:

$$F_M = \frac{P_6}{1 + P_6} \quad \text{with} \quad P_6 = j \cdot \frac{f}{4\,\mathrm{Hz}}$$

and

$$F_{Lp5} = \frac{1}{1 + P_5} \quad \text{with} \quad P_5 = j \cdot \frac{f}{8192\ \mathrm{Hz}}$$

A.2.3. Analog Channels of GPU 05

The GPU 05 contains a lot of filters and amplifiers for signal conditioning of the weak sensor signals. The settings of the notches or low-passes and high-passes always refer to all analog channels simultaneously.

The transfer function F_{cha} of the analog channels of the *GPU 05* is:

$$F_{CHA} = F_N \cdot F_{LP2} \cdot F_{A1} \cdot F_{HP} \cdot F_{A2} \cdot F_{LP3} \cdot F_{LP4} \cdot F_{A3} \cdot F_{HPB1}$$

It follows a detailed description of the single transfer functions.

A.2.4. Low-pass Filter 1

$$F_{LP1} = \frac{1}{1 + p_0} \quad \text{with} \quad p_0 = j \frac{f}{8192\,Hz}$$

The low-pass is switchable by a jumper on the analog board. This filter is implemented off standard.

A.2.5 Notch Filter

The GPU 05 can have up to 3 notch filters which may have center frequencies as listed below. The transfer function of the notch filters is:

$$F_N = \frac{1}{1 + \frac{1}{q\left(\sum_{i=1}^{k} s_i \frac{p_i}{1 + p_i^2}\right)}}$$

$$\text{with} \quad q = 5, \quad p_i = j\frac{f}{f_{N_i}}$$

$s_i = 0$ if Notch_i switched off

$s_i = 1$ if Notch_i switched on

and k is the number of notches.

The following frequencies exist for f_{N_i} : 16.66, 50, 60, 150, oder 180 Hz.

A.2.6. Switchable Low-pass Filter 2 and 4

$$F_{LP2} = F_{LP4} = \frac{1}{1 + p_3} \quad \text{with} \quad p_3 = j\frac{f}{f_{LP}}$$

The following frequencies are adjusted for f_{LP} depending on the selected band:

Band	1	2	3	4 / 5
f_{LP}	8041 Hz	252.5 Hz	8.033 Hz	0.2525 Hz

A.2.7. Amplifier 1

The amplifier 1 is always adjusted to $F_{A1} = 1$.

A.2.8. High-pass Filter

$$F_{HP} = \frac{p_4}{1 + p_4} \quad \text{with} \quad p_4 = j\frac{f}{f_{HP}}$$

f_{HP} is adjusted depending on the selected band:

Band	f_{HP}
1 / 2 / 3	3.98 Sec
4 / 5	2048.3 Sec

A.2.9. Amplifier 2

The possible settings for the amplifier 2 are:

$$F_{A2} = 1$$

or

$$F_{A2} = 16.$$

depending on the selected pregain.

A.2.10. Low-pass Filter 3

The low-pass filter 3 has the transfer function:

$$F_{LP3} = \frac{1}{1 + a_1 p_5 + a_2 p_5^2} \quad \text{with} \quad p_5 = j\frac{1}{8192\ \text{Hz}} \quad \text{and} \quad \begin{matrix} a_1 = 0.630 \\ a_2 = 0.991 \end{matrix}$$

A.2.11. Amplifier 3

The 3rd amplifier F_{A3} is set dynamically depending on the measurement value possible gains are 1, 4, 16 or 64. The gain is contained in the 3rd byte of the *GMS05* time series and the user therefore must not care about this.

A.2.12. High-pass filter for Band 1

Some GPU 05 systems have a 800 Hz high-pass filter. In case it is implemented and switched on, its transfer function is:

$$F_{HPB1} = \frac{p_8}{1+p_8} \cdot \frac{1}{1+\frac{1}{p_8}+\frac{1}{p_8^2}} \quad \text{with} \quad p_8 = j\frac{f}{800\ \text{Hz}}$$

The high-pass filter F_{HPB1} is switched off for the bands 2-5 and may only switched on when band 1 is selected. In case it is switched off its transfer function is

$$F_{HPB1} = 1.$$

A.2.13. Overall Transfer Function of Electric Field Channels

The following formula describes the overall transfer function of the electric filed channel of the *GMS05*:

$$\frac{V_E}{E} = F^E = G_E \cdot d \cdot F_E \cdot F_N \cdot F_{LP2} \cdot F_{A1} \cdot F_{HP} \cdot F_{A2} \cdot F_{LP3} \cdot F_{LP4} \cdot F_{A3} \cdot F_{HPB1}$$

A.2.14. Overall Transfer Function of Magnetic Field Channels

The following formula describes the overall transfer function of the magnetic filed channel of the *GMS05*:

$$\frac{V_H}{H} = F^H = 0.8\frac{\text{V}}{\text{nT}} \cdot F_M \cdot F_{LP5} \cdot F_N \cdot F_{LP2} \cdot F_{A1} \cdot F_{HP} \cdot F_{A2} \cdot F_{LP3} \cdot F_{LP4} \cdot F_{A3} \cdot F_{HPB1}$$

A.2.15. A/D Converter

When using the *GMS05* the data is stored in 4 Byte words. The maximum input voltage is

$$V_{inMax} = \pm\ 10\ \text{V}$$

The 4th byte is always zero. The resoltion of the *GMS05* is 22 Bits. This is achieved by a 16 Bit ADC and a 6 Bit auto gain range amplifier which is controlled by the ADC. By this means the smallest voltage step referred to the input is:

$$1\ \text{LSB} = \frac{10V}{2^{21}} = 4,768\upsilon V$$

Due to the influence of the round robin scheme of the ADC the channels are effected by a phase shift. This phase offset depends on the frequency band and the channel number. The phase offset for the highest frequency (HFreq) of a channel in respect to the calibration channel in the band are:

Band	1	2 / 3 / 4	5
channel 1	$\Delta\varphi$=10°	$\Delta\varphi$=2.5°	$\Delta\varphi$<1°
channel 2	$\Delta\varphi$=20°	$\Delta\varphi$=5°	$\Delta\varphi$<1°
channel 3	$\Delta\varphi$=30°	$\Delta\varphi$=7.5°	$\Delta\varphi$<1°
channel 4	$\Delta\varphi$=40°	$\Delta\varphi$=10°	$\Delta\varphi$<1°
channel 5	$\Delta\varphi$=50°	$\Delta\varphi$=12.5°	$\Delta\varphi$<1°
channel 6	$\Delta\varphi$=60°	$\Delta\varphi$=15°	$\Delta\varphi$<1°
channel 7	$\Delta\varphi$=70°	$\Delta\varphi$=17.5°	$\Delta\varphi$<1°
channel 8	$\Delta\varphi$=80°	$\Delta\varphi$=20°	$\Delta\varphi$<1°

The highest frequencies of the bands are:

Band	1	2	3	4
HFreq	8192 Hz	256 Hz	8 Hz	0.25 Hz

The phase offset for other frequencies than the highest frequency of a band is:

$\Delta\varphi_f=\Delta\varphi*$(frequency/HFreq[band]).

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